

INDUSTRY REPORT

99/11

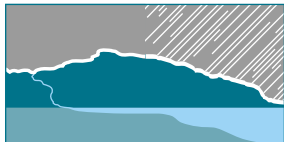
MANAGING SEDIMENT SOURCES AND MOVEMENT IN FORESTS: *The Forest Industry and Water Quality*

NOVEMBER 1999



Jacky Croke
Peter Wallbrink
Peter Fogarty
Peter Hairsine
Simon Mockler
Bob McCormack
Jim Brophy

COOPERATIVE RESEARCH CENTRE FOR



CATCHMENT HYDROLOGY

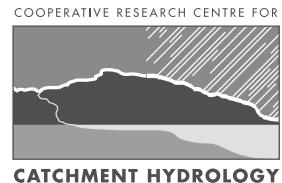
Managing Sediment Sources and Movement in Forests: The Forest Industry and Water Quality

by

**Jacky Croke^{1,2}, Peter Wallbrink^{1,2}, Peter Fogarty³, Peter Hairsine^{1,2}, Simon Mockler^{1,2,4},
Bob McCormack⁵, and Jim Brophy^{1,2}**

¹CRC for Catchment Hydrology ²CSIRO Land and Water ³Soil and Land Conservation Consulting (SLCC)

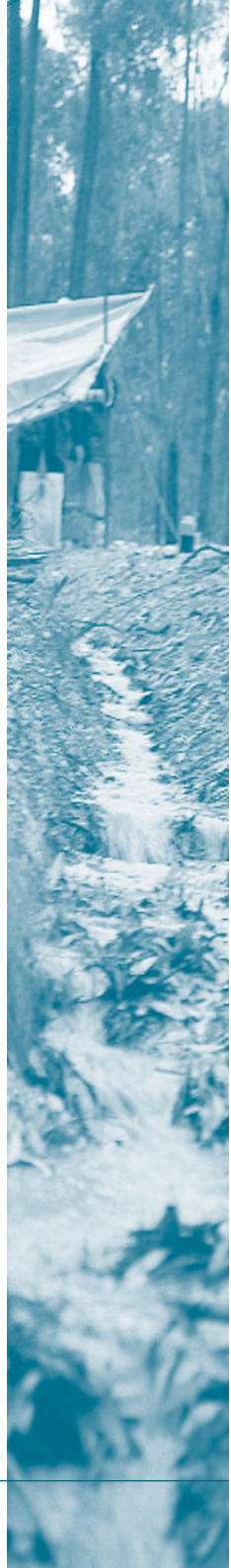
⁴The University of Melbourne ⁵CSIRO Forest and Forest Products



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Cooperative Research Centre for Catchment Hydrology
Centre Office: Department of Civil Engineering,
Monash University, Clayton, Victoria 3800
Australia.

Phone: (03) 9905 2704

Fax: (03) 9905 5033

Website: <http://www.catchment.crc.org.au>

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- Jacky Croke
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- Rob Vertessy
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- How much Rainfall becomes Runoff?
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- Managing Urban Stormwater Using Constructed Wetlands

Foreword

This Industry Report is one of a series prepared by the Cooperative Research Centre (CRC) for Catchment Hydrology to help provide agencies and consultants in the Australian land and water industry with improved ways of managing catchments. Since we published our first CRC industry report in 1997, the response has been overwhelming. It is clear that land and water managers appreciate material written specifically for them.

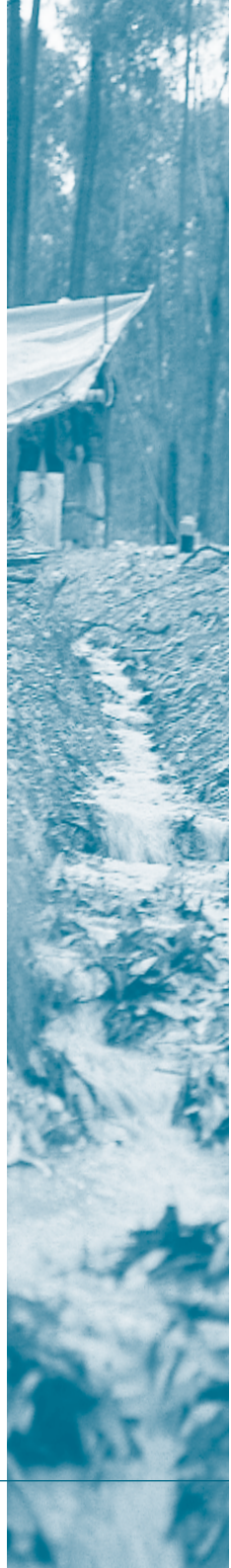
Through this series of reports and other forms of technology transfer, industry is able to benefit from the Centre's high-quality, comprehensive research on salinity, forest hydrology, waterway management, urban hydrology and flood hydrology. Publication of new CRC industry reports is usually accompanied by a series of industry seminars, which further assist in the assimilation of the material.

This particular Report presents key findings from Project FO1 in the CRC's forestry research program entitled, 'Sediment sources and movement in forestry environments'.

The CRC welcomes feedback on the work reported here, and is keen to discuss opportunities for further collaboration with industry to expedite the process of getting these research outcomes into practice.

Russell Mein

Director, CRC for Catchment Hydrology





P r e f a c e

This report presents an overview of our research findings on the management of sediment sources and delivery pathways in forestry environments. Efficient communication of such research outcomes will help forest managers and catchment management agencies to more effectively protect water quality in their catchments. This CRC Industry Report is designed to provide industry practitioners with up-to-date and accurate information for managing forest sediment processes.

The work reported here is the result of cooperative research between the CRC for Catchment Hydrology; CSIRO Land and Water; NSW Department of Land and Water Conservation; Department of Natural Resources and Environment, Victoria; CSIRO Forests and Forest Products; and State Forests of NSW.

A C K N O W L E D G M E N T S

The authors of this report represent the main project team of the CRC's Project FO1 'Sediment Sources and Movement in Forestry Environments'. Many of our colleagues also provided a great deal of assistance and contributed to the progress of the research program. The field experiments undertaken within this project required large field crews, comprising people from the participating agencies, all of whom contributed to making this project possible.

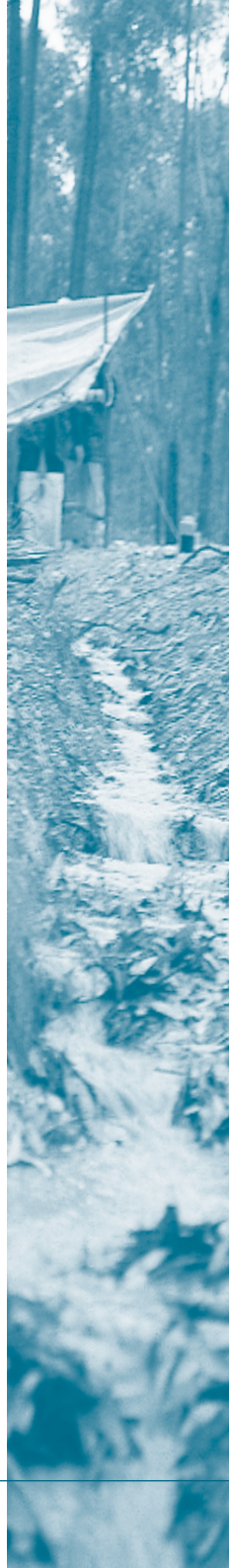
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Appropriate siting of unsealed forest roads is critical in reducing sediment and nutrient loads to streams.

INTRODUCTION

Timber harvesting causes visible soil and vegetation disturbance, and is often regarded as having a significant effect on downstream water quality. In most states, a regulatory framework governs timber-harvesting operations - 'codes of forest practice' and other instruments prescribe a range of management practices to minimise the impact of operations on water resources. Despite major changes to state regulatory frameworks over the past 5 years, the question 'does logging have an impact on water quality?' has remained unanswered.



Water quality is a significant issue in all catchments: the impact of logging practices must be minimised through appropriate, best available management practices.

The CRC for Catchment Hydrology Project FO1 'Sediment sources and movement in forestry environments' has contributed to the collection and analyses of critical field data to further our understanding of logging and water quality issues, and provide managers with practical solutions.

As this report demonstrates, water quality protection in Australia's forested catchments can only be achieved through effective management of both sediment sources and sediment-delivery pathways.

LIMITATIONS OF PREVIOUS RESEARCH APPROACHES

Until recently, the impact of forest harvesting practices on water quality was largely assessed through two research approaches:

1. In-stream measurement of sediment concentration and turbidity at a catchment outlet, usually involving a paired-catchment approach, with monitoring before and after the disturbance period.



Post-harvest burn in Victoria - fire and soil disturbance are among the most common disturbances associated with logging



Heavy logging machinery causes soil and vegetation disturbance, especially during wet weather

2. Small-plot measurement of erosion rates from specific landscape elements such as roads or tracks (e.g. snig tracks and log-access tracks) and general harvesting area (GHA) (Figure 1). Scaling approaches (i.e. taking results from small-plot areas for catchment-scale application) or modelling are then used to predict likely changes in catchment water quality due to forest harvest disturbances.

While providing useful insights into forest-erosion processes, both approaches have inherent limitations.

The *in-stream monitoring approach* is often referred to as a 'black box' approach - data from the outlet is interpreted without any understanding of processes and rates of sediment generation and delivery throughout the catchment. The main difficulty lies in relating changes in sediment load measured at the outlet to forest harvesting on the hillslopes. Increased turbidity at the catchment outlet may, in fact, be related to increased channel erosion due to changed streamflows after harvesting, and not necessarily to hillslope erosion or delivery rates. The problem is particularly complex in

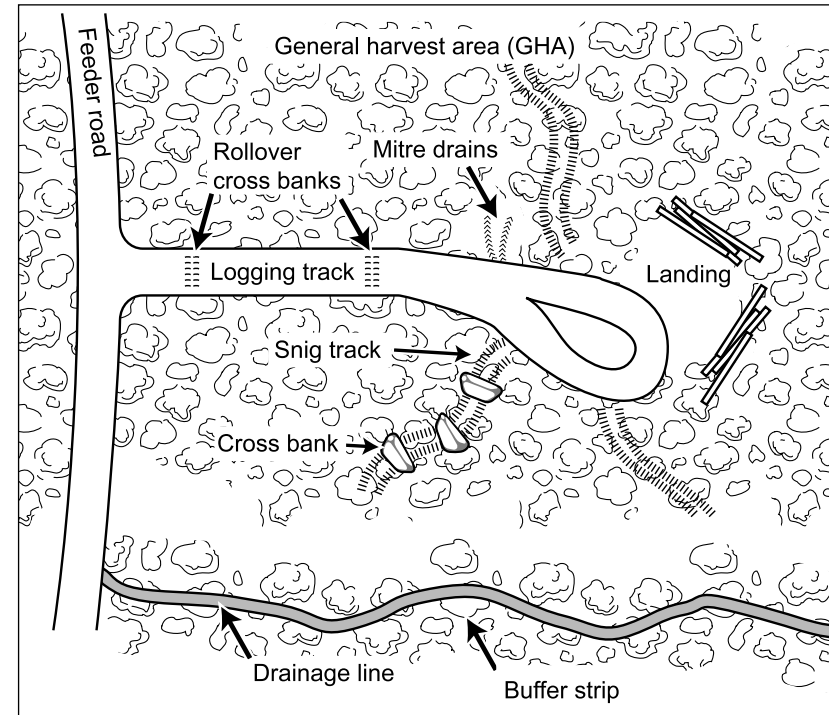


Figure 1: Main 'landscape elements' within a harvested forest - forest road, snig track, general harvesting area (GHA), log landing, cross banks, and streamside buffer-strip

mixed land-use catchments, where it is almost impossible to separate sediment contributions from different landuse practices and sources.

Difficulties with the *erosion-plot approach*, on the other hand, arise from the scale of analysis. Broad-scale processes such as erosion, deposition, and redistribution are often not represented at a small scale. For example, not all of the sediment eroded from a particular hillslope will be delivered to the stream. Many plot-based experiments are too small to measure these redistribution and storage processes. Consequently, erosion rates and potential delivery rates to streams tend to be overestimated.

Recent advances in both research approaches have provided us with more effective techniques to investigate the relationship between timber harvesting and water quality. Catchment-scale studies have benefited from the use of *sediment tracers*, which can be used to ‘fingerprint’ sediment sources within the catchment. Erosion studies are now carried out at larger plot-scales so that sediment storage and redistribution processes can be quantified, resulting in a more accurate assessment of delivery rates and hillslope contributions to streams.



Major landscape elements in managed forests include roads and tracks (above), general harvesting areas (top right) and log-landings (bottom right)



Logged general harvesting area following regeneration burn with retention of some canopy for seed and habitat protection



Bulldozer on log-landing, an area used to store logs for transport to mills

CRC RESEARCH FRAMEWORK

The CRC specifically focused its research on issues that could be easily transferred to forestry environments elsewhere. We sought to identify and locate critical processes and pathways of sediment sources and movement, and use the data to offer solutions and guidelines for improving forestry operations and management. This involved obtaining data on three core issues:

1. **Sediment sources** and their proximity to streams. Not all parts of a disturbed forest generate sediment and runoff equally. We needed to determine the relative contributions from a range of sources, and map their location relative to streams.
2. **Sediment-delivery patterns or pathways** from source to stream, especially the potential for storage on hillslopes, in erosion control structures



Roads are a key factor in determining sediment delivery pathways in managed forests

draining roads and tracks, and in near-stream areas such as buffer strips. Not all sediment eroded from a particular source will be delivered to the stream or catchment outlet. Sediment removed from one source may be redistributed elsewhere on the hillslope. We needed to understand sediment delivery and storage patterns in order to identify the pathways affecting in-stream water quality.

3. The effect of **best management practices** on sediment production and delivery. Best management practices, if successful, can reduce the impact of forest harvesting practices on water quality. We needed to determine whether existing measures were effective and, if not, how to improve them.



General harvest area in the south-east forests of NSW

The emphasis of our research was not only on soil loss or erosion rates, but also on *sediment-delivery pathways* - the routes by which sediment reaches the stream network. In other words, water pollution in logged forests can only occur when there are:

- sources of sediment and pollutants
- delivery pathways which transfers this material to the stream network
- ineffective management practices being applied within the catchment

PROJECT OBJECTIVES

The specific objectives of the CRC research project were to:

- determine the relative contributions of sediment and runoff from source areas in selected forestry catchments
- describe the factors that influence rates of sediment and nutrient movement, including the degree of disturbance, soil properties, rainfall intensity, and vegetation recovery
- evaluate the design and effectiveness of prescriptive forestry measures, including buffer strips and road-drainage structures designed to trap sediment from hillslope sources and prevent it entering drainage lines

DATA COLLECTION

The project had a strong field component, combining onsite, plot-scale, rainfall-simulator experiments with radionuclide-tracer experiments. These were complemented by field mapping, Geographic Information System (GIS) analyses, and modelling to predict outcomes at the catchment scale and under different disturbance scenarios. Combining erosion-plot studies with tracer studies represents a unique scientific approach, which has proved to be among the best available for evaluating the impact of forest operations on water quality.

Study sites

Throughout the project (July 1996 - July 1999), we measured runoff and sediment production rates at 22 sites in native forests extending from coastal northern NSW to the mountain ash forests of Victoria (Figure 2).

These sites are located within Australia's largest - and most intensively managed - area of native eucalypt forests. It includes the Eden and East Gippsland Forest Management Areas (FMAs), which take in more than 350,000 ha across the NSW and Victorian border. The soil types associated with the study sites are summarised in Table 1.

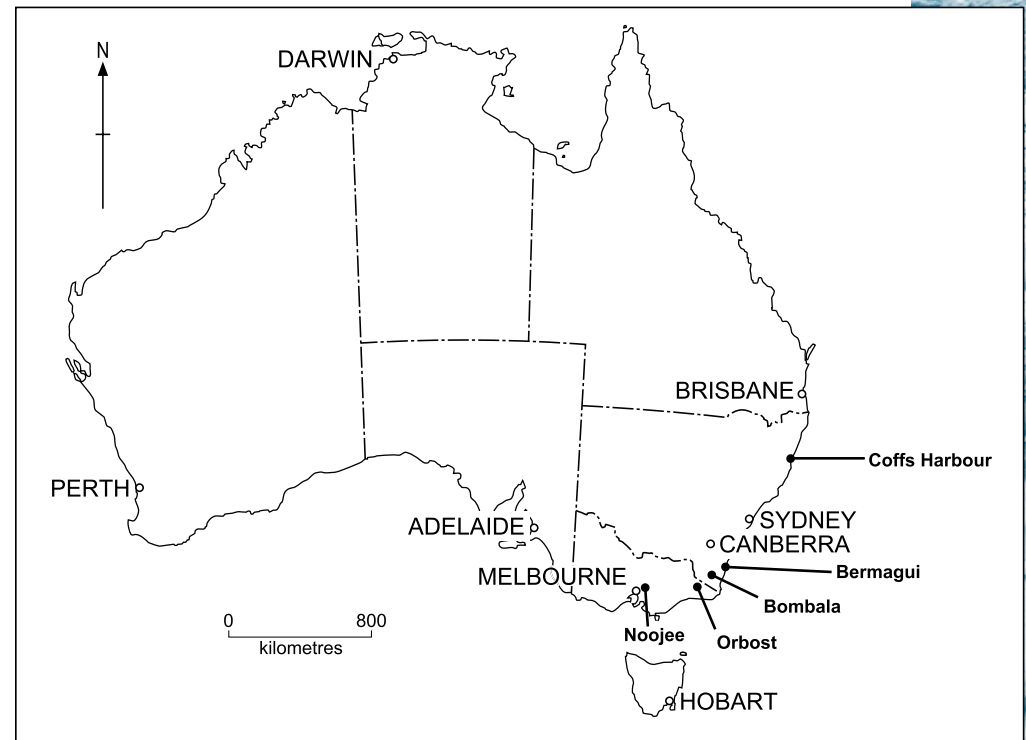
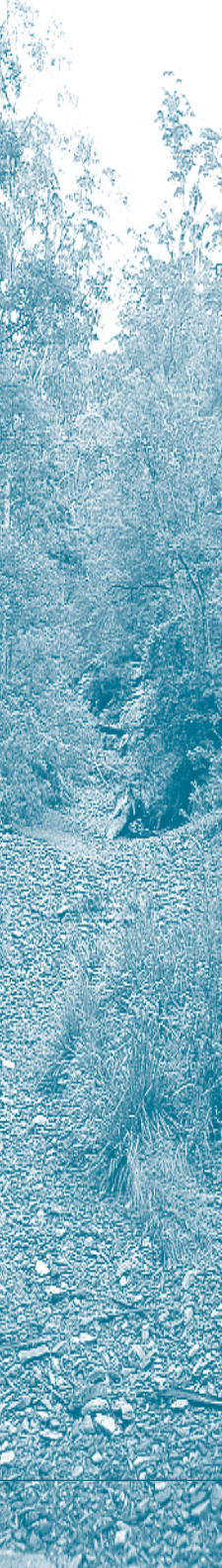


Figure 2: Location of the CRC study sites for forest erosion



Forest Management Area (FMA)	Geology	Soil Description
Eden FMA	Silurio-Devonian coarse-grained granodiorite	Light-coloured, uniformly coarse-textured, weakly structured orthic tenosol
Eden FMA	Silurio-Devonian medium-grained granodiorite	Red-coloured, strongly aggregated soil with a clear textural B-horizon. Red chromosol
Eden FMA	Ordovician metasediments	Gravelly, silty loam with clear textural change. Yellow-brown subsoil overlying weathered siltstone. Yellow chromosol
East Gippsland FMA	Tertiary sands	Coarse sand texture throughout. Tenosol
East Gippsland FMA	Ordovician metasediments	Gravelly silty loam with clear textural change. Yellow chromosol

Table 1: Location and description of soil types and parent-rock geologies at CRC research sites

Many of our field sites are concentrated in the area between Bombala on the Southern Tablelands and Bermagui on the south coast of NSW. The tracer study was carried out in a NSW State Forests catchment near Bombala in the Eden Forest Management Area. We selected the 60 km² Cuttagee Creek catchment in the NSW Murrumbidgee State Forest to investigate sediment production and delivery rates from forest roads, and examine the long-term record (150-200 years) of sediment delivery to coastal and estuarine areas (Figure 3).

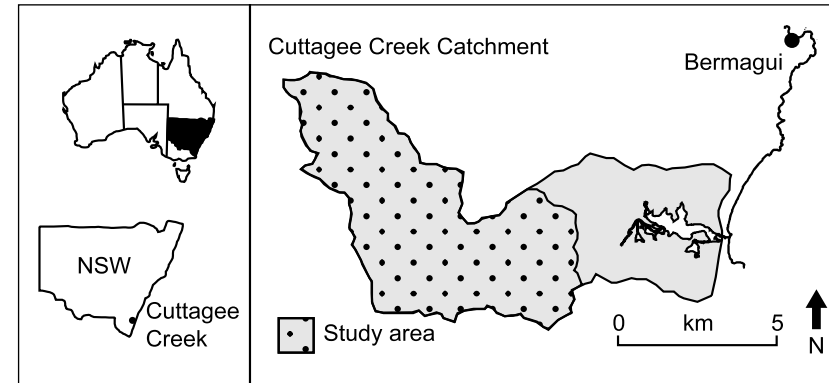


Figure 3: Cuttagee Creek Catchment, a mainly forested catchment draining into Lake Cuttagee near Bermagui, southeastern NSW

Rainfall-simulator experiments

Rainfall simulation has been widely used in soil-erosion research for many decades. It has proven to be a rapid, efficient, and controlled method for collecting field data. Its disadvantages are the size limitations of experimental plots and related costs. Three factors influence the quality of data derived from rainfall-simulator experiments:

1. **Plot size:** A sufficiently large area is required to obtain representative measurements of soil erosion, deposition, redistribution, and storage. We used a combined plot layout that routed material from a snig track onto the general harvest area (GHA) via a cross bank or water bar, resulting in a plot area of about 300 m². To measure sediment production on forest roads, we enlarged the plot size to about 600 m². This allowed us to include the sediment contribution from upslope areas on the cut-side of roads.
2. **Rainfall intensity:** The nozzles used with the rainfall simulator produced three rainfall intensities with a constant drop-size diameter - 45 mm/h, 75 mm/h, and 110 mm/h. These rainfall intensities were converted to storms

of known frequency and duration using *Australian Rainfall and Runoff* (Pilgrim 1987). For example, a 30-minute rainfall event of 45 mm/h intensity represents a 1-in-2 year storm in the Eden Forest Management Area. We consistently ran the storms in a successive sequence from low to high rainfall intensity. While this introduced limitations in terms of sediment depletion, this effect cannot be avoided in studying generation rates under different rainfall intensities.

3. **Rainfall duration:** We selected a rainfall duration of 30 minutes, assuming that this time period represented the rainfall 'burst' that accounts for most of the erosion expected from events of different duration. There was also a logistical constraint in terms the amount of water storage required to simulate events of longer duration.



Rainfall simulation on logged snig track and general harvesting area, Eden Forest Management Area, NSW

Note on units of measurement: Soil loss and yields from simulator studies are expressed throughout this report as event-based yields - i.e. the amount of sediment derived from a rainfall of specified intensity and duration (30 minutes). Event-based sediment yields are expressed as mass per unit area (tonnes per hectare or t/ha) and are not mean annual averages. Soil loss and sediment yields from the tracer studies, however, are expressed as mean annual averages - i.e. tonnes per hectare per year or t/ha/y.

Tracer methodology

To be useful in erosion studies a sediment tracer must be:

- *stable* - not altered by the transport process
- *quantifiable* by routine analytical methods
- *representative* of the sediment body or erosion source



Rainfall simulation along ridgetop road in Cuttagee Creek covering an area of 300-600 m², with a contributing road length of 40 m



One of the nuclear weapons tests carried out between 1945 and 1975 that led to fallout of Caesium-137 across the world. This tracer helps to quantify soil movement in disturbed areas

Caesium-137 (^{137}Cs) satisfies these criteria. ^{137}Cs is a by-product of nuclear weapons testing between 1945 and 1974, when it was injected into the atmosphere during nuclear blasts and became evenly distributed across exposed soils. Once deposited, ^{137}Cs quickly becomes attached to soil particles, even during subsequent soil transport.

^{137}Cs has a half-life of about 30 years. Measurement of ^{137}Cs is usually expressed as Becquerels (*see box*). In undisturbed Australian forest soils, ^{137}Cs is generally found at a maximum concentration just below the soil surface, from where it tails off to barely detectable limits at depths of about 200-250 mm.

Measuring radioactivity

The basic unit of radioactivity is the Becquerel (Bq), which represents one nuclear disintegration per second. A thousand units of disintegration is one kilobecquerel (KBq), while one million is termed one megabecquerel (MBq). These units are sometimes also given with respect to surface area (i.e. Bq/m²) or per mass of soil (i.e. Bq/kg).

In this project, we started with the basic principles of ^{137}Cs methodology, improved them using geomorphic information about harvested catchments, and incorporated the results into a *tracer budget*. Tracer budgets enable us to investigate the post-harvesting redistribution of soil and sediment to a level of accuracy not previously achievable. The methodology we used included:

1. **Defining landscape elements:** We first divided the forest into 5 harvesting elements (see Figure 1).

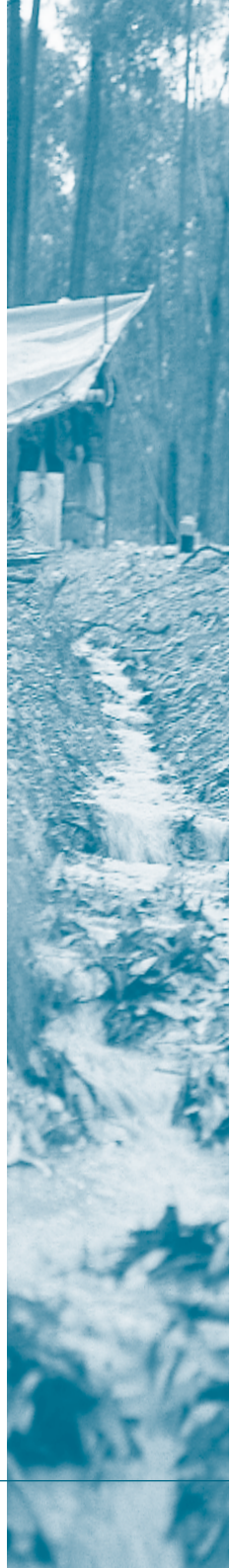
- general harvest area (GHA) - the actual forested area in which logs are felled
 - snig tracks - created by bulldozers as pathways to carry harvested logs to the log landings
 - log landings - locations where logs are stripped of bark and loaded onto trucks
 - cross banks - mounds of earth created from soil material scraped from the surface of snig tracks
 - filter-strips or buffer-strips - intact belts of forest adjacent to drainage and stream lines, which are intended to reduce sediment delivery and maintain stable channel banks
2. **Measuring the ^{137}Cs within these elements:** The ^{137}Cs -level in each of the 5 landscape elements was obtained from soil cores. A similar procedure was used to measure the ^{137}Cs 'reference' level in adjacent, undisturbed native forest of similar slope and aspect to the study site. This reference activity represents the amount of ^{137}Cs that had been deposited, and would have been measured, in that catchment area had no erosion or deposition occurred. In simple terms, ^{137}Cs values in a landscape element below the reference level represent erosion areas, whereas higher values represent deposition areas.
 3. **Quantifying the redistribution of soil and sediment:** The redistribution of soil and sediment between the landscape elements was quantified by comparing the total amount of ^{137}Cs initially present in each landscape element with post-harvesting levels. The pre-harvesting ^{137}Cs level in a landscape element is calculated from the individual surface areas and reference level. The amount remaining in each landscape element after harvesting is calculated from the surface areas and direct measurement of ^{137}Cs in soil cores.

4. **Using the budget to trace soil movement:** When the numbers in the budget are added up, the difference between the pre- and post-harvesting ^{137}Cs levels in each landscape element show us where soil losses and gains have occurred. These differences can then be used to quantify the relative redistribution of material within the landscape, as well as quantify loss rates.

PRESENTING THE RESEARCH FINDINGS

The CRC's research findings are presented in the following pages in terms of the three areas of concern identified earlier in this report:

1. **Sediment sources:** This section provides information on the main sources of runoff and sediment, as well as the factors affecting sediment-generation rates, such as soil type, traffic intensity on roads, and vegetation recovery over time.
2. **Sediment-delivery pathways:** This section defines common delivery pathways and where they occur in a catchment, highlighting the most damaging pathways contributing to water pollution.
3. **Best management practices:** This section looks at existing best management practices and evaluates their effectiveness in stopping sediment reaching streams at hillslope and catchment scales.



I. SEDIMENT AND RUNOFF SOURCES

THE MAIN SOURCES OF SEDIMENT

Some of the landscape elements described earlier (Figure 1) also represent the main sources of runoff and sediment in a logged catchment. These are:

- unsealed roads
- snig tracks
- log landings
- general harvesting areas (GHAs)

The potential impact of these sources must be assessed both in terms of their runoff-generating capacity and erosion rates. Sediment cannot be mobilised and delivered offsite without a transporting agent, such as water or wind. ***Thus, the amount of water generated by each landscape element is a critical factor in determining the amount of sediment that will be carried to a stream.***

RUNOFF CHARACTERISTICS OF SEDIMENT SOURCES

Roads and tracks

The weight of heavy logging trucks and vehicles compacts the soil surface of forest roads and tracks. This compaction results in low water infiltration rates, with the result that roads and track surfaces generate more runoff, at a faster rate, than uncompacted surfaces. Measured infiltration values from roads and tracks range from 0.5-10 mm/h (Figure 4). Because most rainfall intensities are higher than mean infiltration rates on road surfaces, surface flow can be produced even during small rainfall events.



Well-used, unsealed road in the Cuttagee Creek catchment showing runoff entering a mitre drain, used to divert runoff onto the adjacent hillslope



Runoff accumulates quickly on compacted road surfaces even during light to moderate rainfall

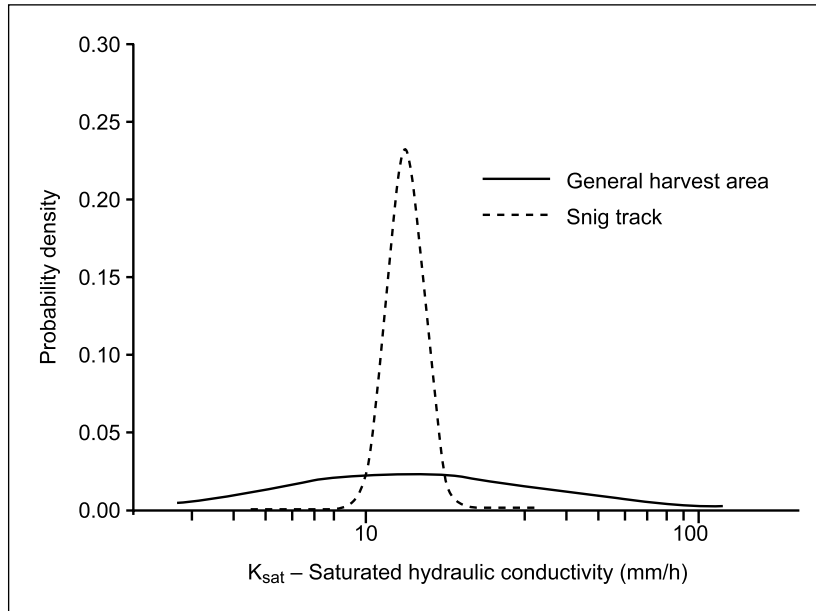


Figure 4: Comparison of saturated hydraulic conductivities (K_{sat}) from a snig track and general harvest area (GHA) within a sandy granite soil area near Bombala NSW. The peaked snig track curve indicates that most sampled values were similar, producing a low standard deviation around a mean value of about 12 mm/h. The much wider, flat curve of the general harvesting area with a larger range of values (high standard deviation), indicates the presence of disturbed areas with low K_{sat} and less-disturbed areas with higher K_{sat} values

More than 80% of the rain that falls onto these surfaces is converted to runoff. These large volumes of water transport sediments through the landscape.

General harvesting areas (GHAs)

General harvesting areas (GHAs) retain a high percentage of vegetation and contact cover. Compared with the smooth surface of roads and tracks, water accumulates and moves more slowly over rough areas, ponding in vegetation and around obstacles. Disturbance by heavy machinery on the general harvesting area is often restricted to small areas, unlike the broader-scale disturbance on tracks and roads.



Runoff being measured in a flume on a road segment in Cuttagee Creek - note water concentration in roadside ditch

Runoff generation is relatively patchy and slow in the general harvesting area - widespread 'sheet flow' is not usually observed. Compared to tracks and roads, general harvesting areas have much higher infiltration rates - for example, a rate of about 150 mm/h was recorded for a sandy granite soil in a general harvesting area near Bombala.

Only about 10-20% of rainfall is converted to runoff in general harvesting areas, limiting sediment transport to short distances (*see next section of this report on sediment-delivery pathways*).

DIFFERENCES IN EROSION RATES: ROADS AND GENERAL HARVESTING AREAS

We compared the relative contribution of sediment from three landscape elements - roads, tracks, and general harvesting areas - within a single catchment in Cuttagee Creek on uniform soils and under comparable rainfall intensities.

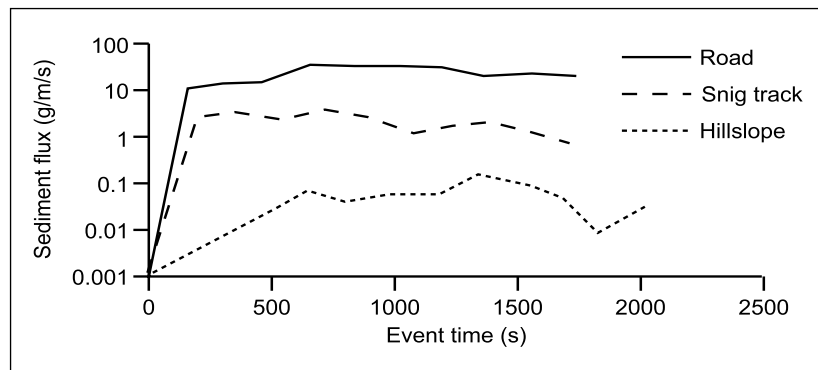


Figure 5: Fluxes of sediment (product of both discharge and sediment concentration) from unsealed forest road, snig track, and general harvesting area, showing differences between these three dominant sources of one order of magnitude (note the log-scale on the y-axis)

Results showed that:

- Unsealed forest roads generated an order of magnitude more sediment than a recently disturbed snig track in the Cuttagee Creek catchment (Figure 5).
- A recently disturbed snig track generated an order of magnitude more sediment than the adjacent general harvesting area in the same catchment for a comparable rainfall intensity (Figure 5).

Sediment yield from each area of road, track, and general harvesting area was limited by the amount of sediment available on the surface before each simulation. Sediment concentrations were high at the start of a rainfall event,

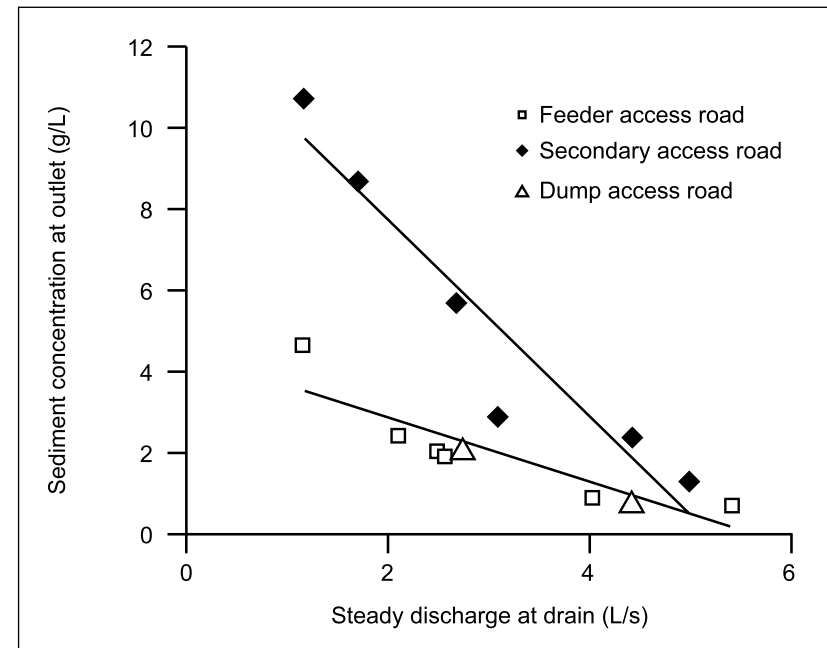


Figure 6: Sharp decline in sediment concentrations on all road surfaces as a rainfall event progresses, indicating that the material available for flow transport decreases as the event continues. (Secondary access roads are the most frequently used and maintained, whereas feeder and dump access roads are used only temporarily and later abandoned)

but declined as material was progressively washed off these surfaces and not replenished. Likewise, sediment concentrations did not increase as we increased the intensity and volume of water. The larger volume of water generated during higher intensity storms would have been capable of transporting a higher sediment load, had more sediment been available (Figure 6).

Factors that influence the amount of sediment available for mobilisation include traffic volume on roads and tracks, the sequence of rainfall events after track closure, and the dominant sediment-transport process (e.g. rill or shallow sheet flow). Often, large stores of material (referred to as 'bulldust') can be found on heavily used road surfaces after long periods of dry weather. This material will be available for transport during the first rainfall event.

DIFFERENCES IN EROSION RATES: UNSEALED ROADS

Unsealed road types within a managed forest area range from well-used, well-maintained roads to those used infrequently or abandoned. We examined the differences in sediment-production rates of three road classes in the Cuttagee Creek catchment near Bermagui NSW, for both 1-in-10 and 1-in-100 year storms.

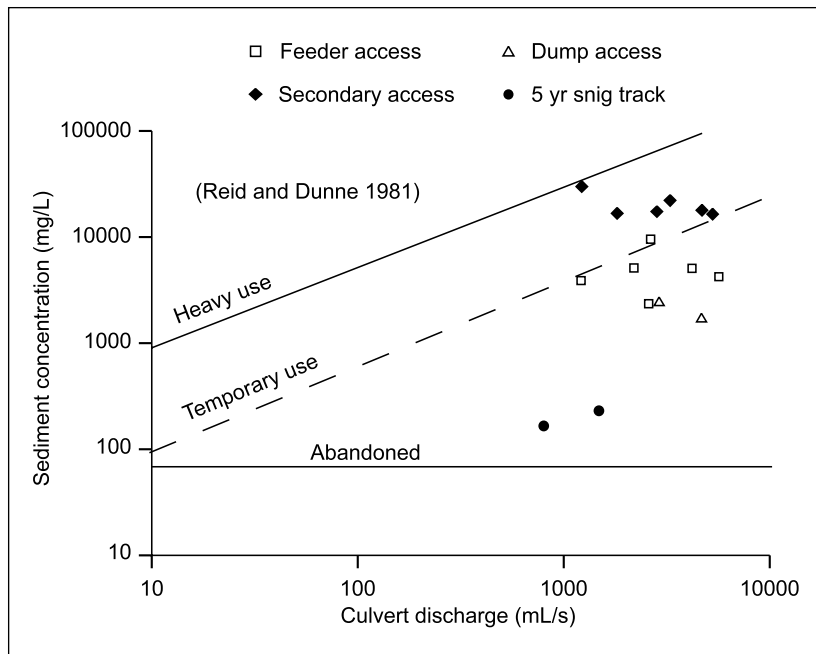


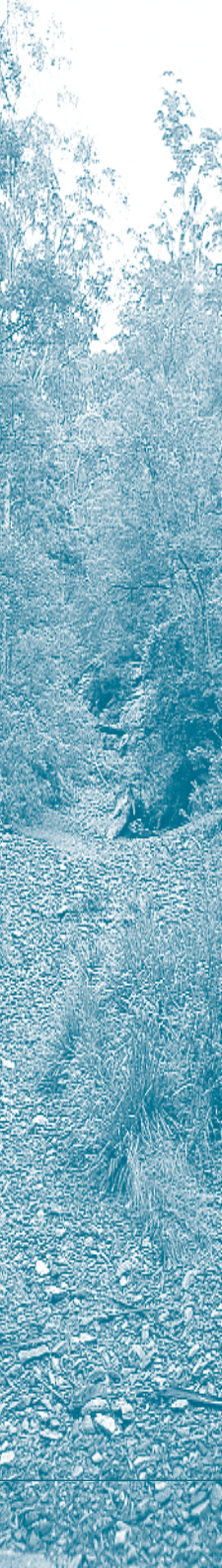
Figure 7: Comparison of sediment concentrations and discharge from well-used and abandoned roads and tracks in the Cuttagee Creek Catchment (point data). Values are plotted relative to sediment concentration and discharge values reported by Reid and Dunne (1981) for roads in the Clearwater Basin, Oregon USA. Heavily used roads were classified as having four loaded logging trucks per day, similar to the rate estimated for the Cuttagee Catchment.



The dramatic effect of traffic intensity on sediment production from forest roads - a heavy water-truck pounds the surface of an experimental site in Cuttagee Creek, near Bermagui

Key findings

- Sediment concentrations in road runoff were between 5 and 8 times higher on well-used roads than abandoned ones (Figure 7).
- Roads with higher intensity traffic have greater volumes of loose material available at the surface. This is replenished after each rainfall event by continuing vehicle usage.
- Roads used infrequently or abandoned have little available sediment and, in the absence of traffic, are minor sources of sediment. The only detachment processes creating loose sediment are raindrop splash and surface overland flow.



Landscape Element	Surface area (% of total)	Activity (Bq/m ²)	Total pre-harvest ¹³⁷ Cs activity (MBq)	Total post-harvest ¹³⁷ Cs activity (MBq)	Difference (MBq)	Losses and gains (% of total)
Snig tracks	17	187 ₉₀	10.9	4.2	-6.6 _{3.2}	-11 ₅
Log landings	3	153 ₉₀	1.6	0.5	-1.1 _{0.6}	-2 ₁
GHA	74	525 ₃₂	45.2	48.1	2.9 _{0.2}	5 _{0.3}
Filter-strip	6	740 ₉₀	3.4	5.1	1.7 _{0.2}	3 _{0.3}
Cross banks			0	1.2	1.2 _{0.6}	2 ₁
Reference		490 ₉₀				
Total	100		61.1 _{3.1}	59.0 _{3.6}		
Unaccounted					2.1	

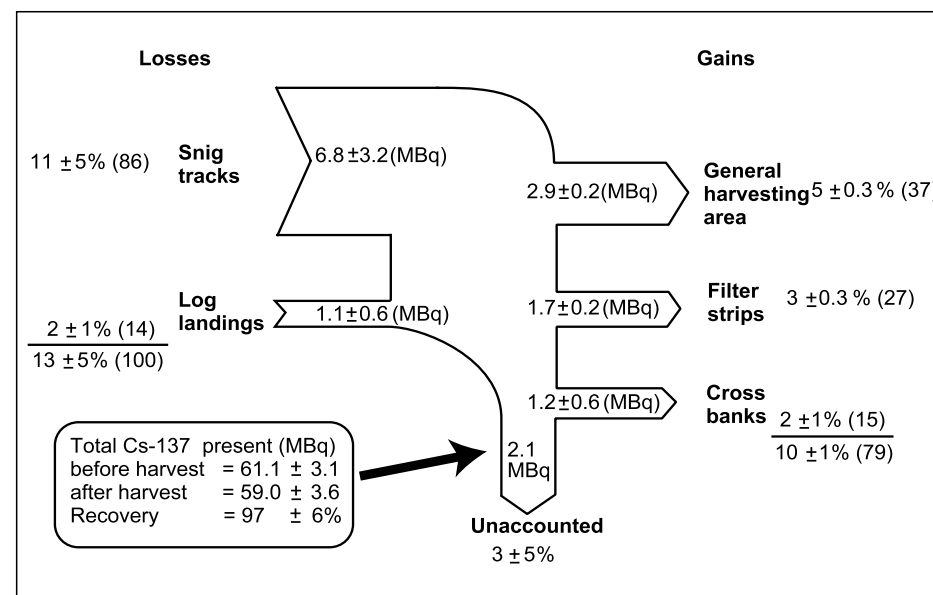
Table 2: Relative surface areas and radioactive ¹³⁷Cs levels in different harvesting elements at Bondi State Forest NSW. The gains and losses of ¹³⁷Cs quantify relative gains and losses of soil and sediment from the different elements. The subscript denotes standard errors associated with the measurement of each value

Figure 8 (below): Tracer-based sediment budget showing the partitioning of soil material eroded ('losses') and redeposited ('gains') between landscape elements at Bombala, NSW. Of the total input of Caesium-137 about 13% was redistributed. The areas from which the redistributed tracer originated are shown as losses (left), and the areas in which the tracer was deposited are shown as gains (right). Tracer levels retained within each element are shown as MBq units within the respective arrow

¹³⁷Cs TRACER EVIDENCE: SEDIMENT LOSSES AND GAINS

Measurement of radionuclide-tracers in the different landscape elements and their incorporation into a 'tracer budget' complemented the data obtained from rainfall simulation studies.

About 13% of the ¹³⁷Cs initially present in the test catchment was redistributed between landscape elements after harvesting. These can be considered as internal 'losses' (Figure 8). Of these losses, around 11 % came from snig tracks and 2% from log landings (Table 2). Snig-track erosion rates were about 70 t/ha/y (tonnes per hectare per year). Erosion rates from the log landings were about 120 t/ha/y, although the total log landing area was small.



Major areas of sediment deposition were identified as 'gains' within the tracer budget. Of the 10% of ¹³⁷Cs accounted for in depositional elements, 5%, 3%, and 2% were located in the general harvesting area, buffer-strips, and cross banks, respectively.

The tracer results confirmed the rainfall-simulator study findings that snig tracks and log landings are major sources of sediments.

HOW DOES SOIL TYPE AFFECT EROSION RATES?

Soil type is known to influence the erosion process, particularly runoff generation and sediment yield. Soil type may also affect the main sediment-transport mechanism - whether that is sheet flow; wide, shallow flow; or the more concentrated, deeper flow found in rills. (*Rills* are small gullies or channels less than 10 cm deep, which often form in non-cohesive, easily detached soils.)

We examined differences in soil loss and sediment yield (see box) from three soil types representative of the Eden Forest Management Area in

Erodibility

The erodibility of a soil, is a measure of its susceptibility to detachment and transport by erosion agents. It is related to soil properties such as texture, structural stability, organic-matter content, clay mineralogy, and chemistry. Properties such as organic matter can change over time due to landuse practices. Erosion or removal of surface layers can expose more, or less, erodible subsoils so that the erodibility of a soil can change over time. The main erosion processes are infiltration, runoff, detachment and transport by both raindrops and overland flow.

southeastern NSW (see Table 1 for description of soil types). Figure 9 depicts the layout of the experimental plot and shows erosion rates (as tonnes per hectare per 100-year event) for each area of disturbance on two sites of contrasting soil type - the red chromosols of the granodiorite (known locally as red granites), and the gravelly chromosols of the metasediments.

Key findings

- There was a five fold difference in soil losses from snig tracks on the granitic soils compared with losses from the more gravelly soils of the metasediments (Figure 9).
- Sediment on the granite sites was transported in rills that had formed in the wheel ruts of logging machinery. Sediment from the metasediment

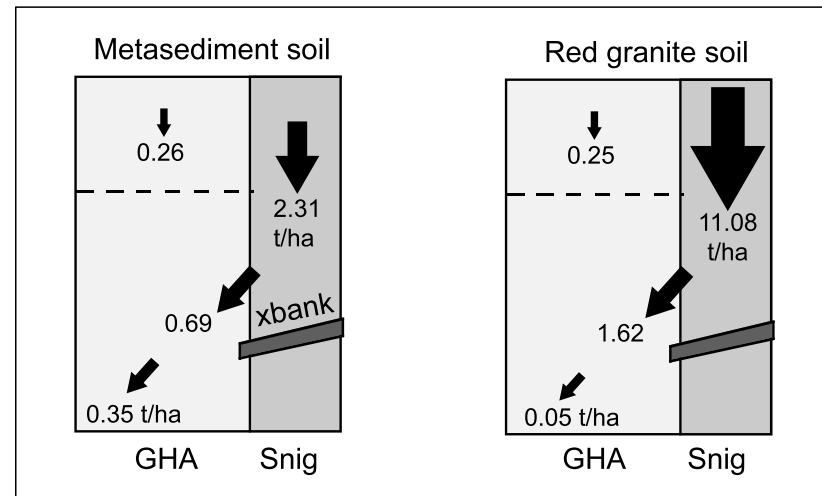


Figure 9: Soil loss (e.g. from snig tracks) and sediment yield (from the entire plot of 300 m²) for two sites of contrasting soil type in the Eden Forest Management Area, southeastern NSW. High soil losses occur on snig tracks in both soil types, particularly the granite site, but soil loss reduces significantly as runoff is routed from the snig track, through a cross bank, and onto the general harvesting area (GHA). The metasediment site contributes the most sediment, indicating that high sediment yields are not necessarily associated with highly erodible soils.

sites was transported in wide, shallow sheet flow, which had less available energy for transporting high sediment loads.

- Figure 9 shows that the soils on the metasediment sites contributed the greatest sediment yield at the plot exit, and thus may represent the greatest 'risk' to stream water quality (see box).
- Soils with low cohesion and resistance - such as granite-derived soils - are the most easily detached, but they are also less easily transported. Thus, a

Soil loss and sediment yield - an important distinction

The distinction between soil loss and sediment yield has significant implications for forest management practices and water protection.

Soil loss is defined in the scientific literature as the amount of soil lost in a specified period over an area of land that has experienced a net soil loss. It is expressed as mass per unit area e.g. t/ha or kg/m². Soil loss is used in discussing onsite effects, such as soil fertility and forest productivity.

Sediment yield refers to the amount of sediment crossing a boundary - such as the edge of a plot, hillslope, or catchment outlet. It is expressed as total mass or mass per unit area e.g. kg or kg/m². Sediment yield is important in terms of offsite erosion effects such as water pollution, and stream or reservoir siltation. Not all soil losses become sediment yields, as some soil particles are deposited on hillslopes or in erosion-control structures. Most landscapes have some areas that show a net soil loss over time, and some areas that show a net soil deposition. The difference between the two is the amount of soil leaving the area - termed sediment yield in this report.

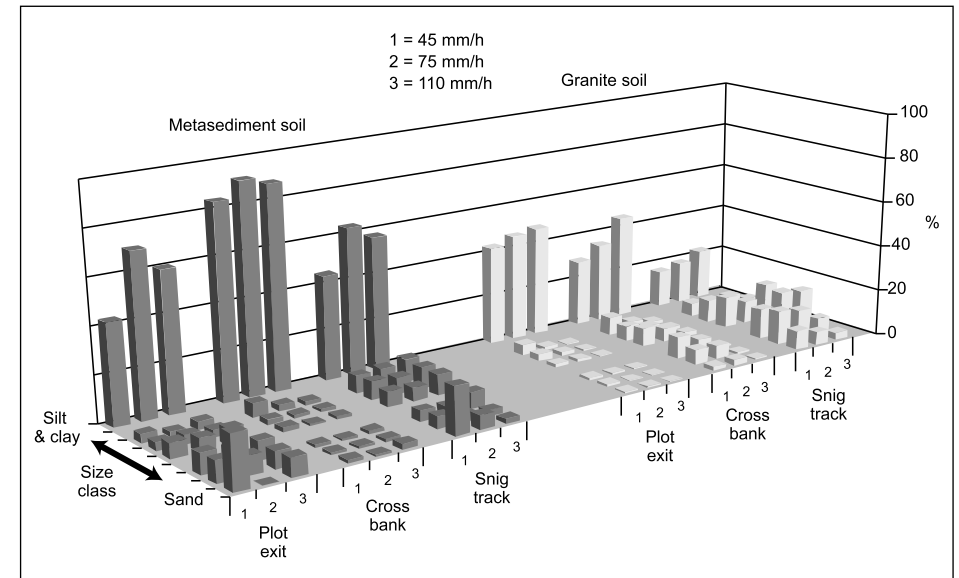


Figure 10: Comparison of percentage of fine-grained silt and clay transported through each area of disturbance - snig track, cross bank, and plot exit - for sites on the red granite and metasediment soils. Note the high percentage of silt and clay in runoff from the site with metasediment soil, which explains the higher sediment yield from sites on this soil type.

higher percentage of eroded material remains onsite, stored in cross banks or on the hillslope.

- Soils such as those on metasediment sites consist of a higher percentage of fine-grained silt and clay material (Figure 10). This material is easily transported and remains in suspension until runoff infiltrates.

Offsite impacts such as water pollution and stream siltation require effective management of sediment yield. High sediment yields are not necessarily derived from the most highly erodible soils. Managers carrying out erosion-hazard assessments need to take into account both the potential for detachment of soil particles, and the potential for this sediment to reach receiving waters.



Regrowth on a five year old snig track on sandy granitic soils, Bombala, NSW. These sites produce little runoff and sediment due to vegetation regrowth and recovery of surface-soil permeability.

HOW LONG DO TRACKS AND LOGGED AREAS TAKE TO RECOVER?

Periods of intensive forest activity, such as road and track construction and timber removal, coincide with maximum soil and vegetation disturbance. In the native eucalypt forests of southeastern Australia, patchwork-pattern logging is planned on an inter-harvesting cycle of about 20-40 years. Thus, within a logged catchment, a range of logging coupes in various states of recovery and regeneration can be found.

Recovery can be assessed using a range of indices, such as:

- soil compaction
- infiltration rates
- surface-erosion rates

We measured changes in these properties on nine study sites with different recovery periods since logging - ranging from six months to five years - in the Eden Forest Management Area of NSW.

Key findings

- Compaction on the snig track showed no significant recovery over the five years since construction, demonstrating the long-term effect of machinery compaction on soil structure.
- Hydraulic conductivity on the snig tracks increased with time, showing some recovery and improvement of surface-soil structure and drainage/permeability (Figure 11).
- Sediment-production rates on the snig tracks declined with recovery time over five years (Figure 12).

As erosion rates are highest during the early stages of site recovery, protective measures must be put in place during and immediately after disturbance to reduce offsite impacts, such as stream pollution.

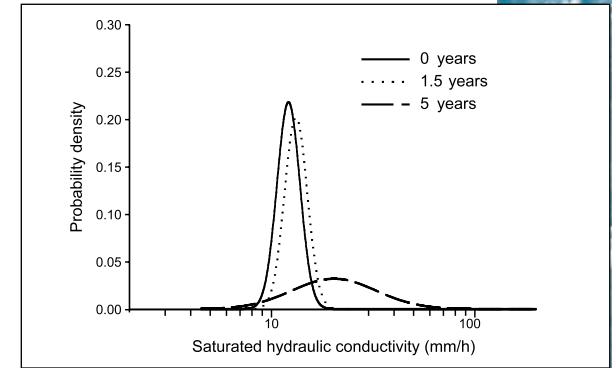


Figure 11: Changes in saturated hydraulic conductivity (Ksat) of snig track on three sites - 6 months, 1.5 y, and 5 y after logging. The curves indicate some recovery in permeability of a site's surface soil over time.

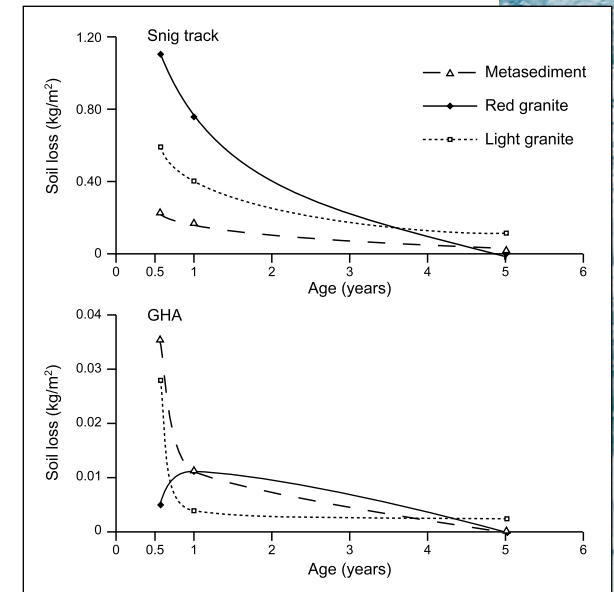


Figure 12: Changes in surface soil losses for snig track (compared to GHA) with time-since-disturbance. The marked reduction in erosion rates with recovery time indicates that erosion-control devices must be in place during the early period of track recovery.

II. SEDIMENT-DELIVERY PATHWAYS

Having identified the dominant sources of runoff and sediment, the next challenge was to determine how this material was being delivered to the stream network.

We also needed to measure the sediment-delivery ratio (SDR) - the proportion of eroded sediment delivered to receiving waters. The SDR is a critical variable in determining the potential impact of harvesting on water quality, and is influenced by both environmental attributes and management practices.

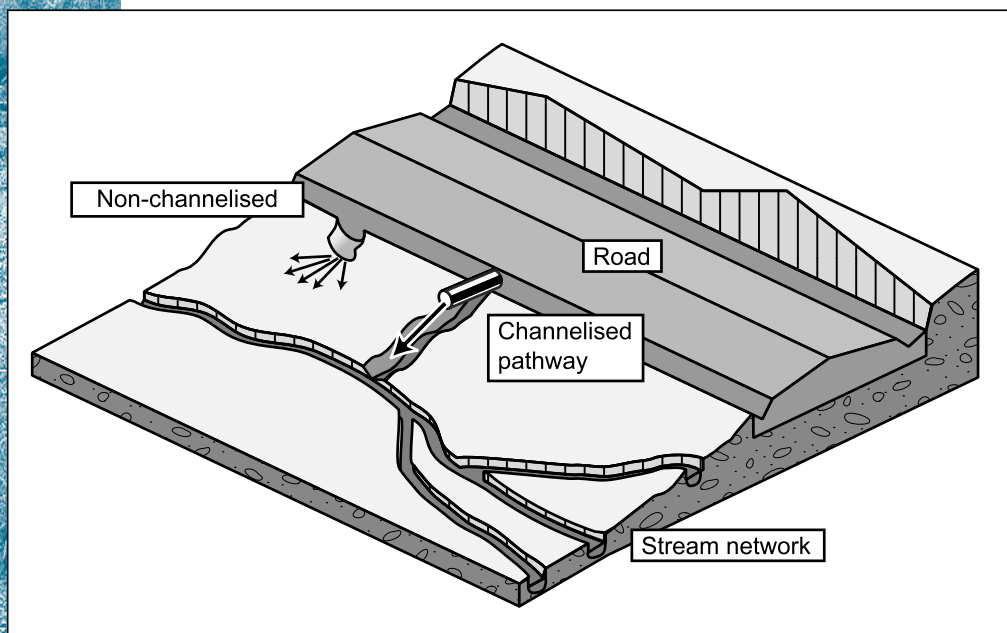


Figure 13: The two main sediment-delivery pathways in forested catchments - channelised or gully pathways that form a distinct channel deeper than 30 cm; and non-channelised pathways, in which flow does not concentrate and water disperses at the outlet of a road or cross bank

Sediment-delivery patterns vary with location and layout of sediment and runoff sources (landscape elements) within the catchment, and with local management practices. Forest roads, for example, have a specific delivery pattern, which is determined by the spacing and location of drainage structures within the catchment.

MAIN PATHWAYS FOR SEDIMENTS TO REACH STREAMS

Sediment-delivery pathways can be broadly categorised as:

- **incised channels or gullies** - where flow is concentrated, resulting in high sediment-transport capacity and runoff delivery downslope
 - **non-channelised pathways** - where water disperses or spreads across the hillslope, reducing flow depth, velocity and, consequently, the ability of the flow to transport sediment (Figure 13)
- These pathways can be further characterised by the degree to which they are linked to the receiving waters, which includes:

- **full channel linkage** - where a gully extends the entire distance from a discharge point, like a drain or culvert, to a stream
- **partial channel linkage** - where the incised pathway terminates some distance down the hillslope, often coinciding with a change in slope towards the valley bottom, or with the presence of an obstruction such as a fallen tree or debris mound
- **no channel linkage** - where the discharge disperses as it leaves the source area and there is no morphological evidence of any concentrated flow (Figure 14). The probability of runoff from these pathways linking with receiving waters depends on their proximity to a stream and the hydraulic

properties of the discharge hillslope (see section on managing non-channelised pathways)

- **direct linkage** - which occurs at a stream crossing or ford, where the road or track directly intersects receiving waters

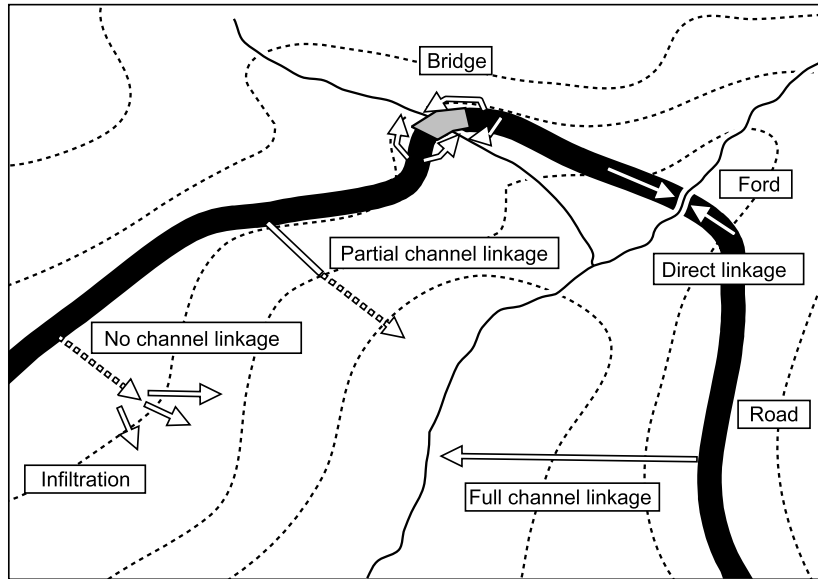


Figure 14: The range of potential linkage categories within a forested catchment - from full channel, partial channel, and no channel linkage, to the direct linkage that occurs at a ford or bridge crossing. These categories can be used to determine the degree to which major sources like roads and tracks, are linked to streams

Predicting the occurrence of channelised pathways

For the Cuttagee Creek catchment in NSW, we classified and mapped the type of delivery pathways and the extent of linkage to streams using the above linkage classes. Geographic Information System (GIS) data layers were used to select representative road segments within the catchment, and we surveyed about 20% of the 75 km road network in detail (Figure 15).



Water discharging from mitre drain and travelling downslope across vegetated surface, where flow quickly spreads and disperses across the hillslope

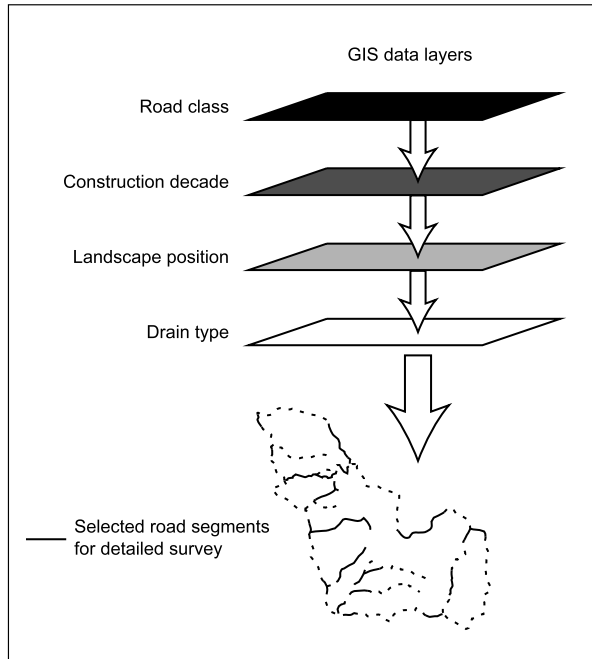


Figure 15: Data layers within a GIS framework can be compiled to select representative road segments for field surveys and mapping

Key findings

- The Cuttagee Creek catchment has an additional 10 km of stream channels or gullies due to gully initiation at road-drainage outlets. These new channels formed in previously un-channelled areas.
- The addition of this 10 km to the total natural channel length leads to a 6% increase in catchment drainage density. Drainage density defines the total length of channels (km) within a unit area of catchment (km²) (Table 3). We know, therefore, that the catchment has more channels now than it had before road construction began in 1964.
- Because of these new channels, some 31% of the natural stream network now receives and carries runoff and associated pollutants from

road-drainage outlets. Because material delivered to channels in the upper catchment is transferred downstream, the potential impact of this sediment is widespread and not confined to the immediate area of gully development.

- Most (83%) gully initiation occurred at relief culverts (Figure 16) draining cut-and-fill roads. Relief culverts are concrete pipes used to divert runoff and sediment from the cut-side of roads to the fill-side. In contrast, about 89% of mitre drains draining ridge-top roads showed no evidence of channel linkage (Figure 17). Mitre drains are extensions of the roadside ditch or table-drain, which direct runoff and sediment onto the adjacent hillslope (Figure 16).

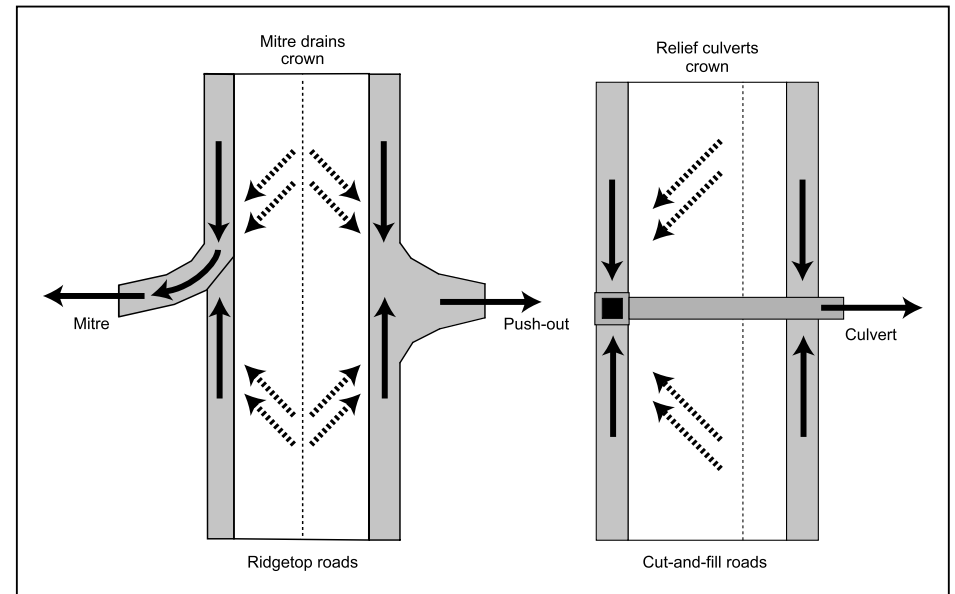


Figure 16: Typical road-drain types used on ridge-top and cut-and-fill roads. Mitre drains are extensions of the roadside ditch used along ridge-top roads to divert runoff onto the adjacent general harvesting area. Push-outs are used similarly in road saddles or topographic lows and bring water from two segments of road to a central draining point. Drainage on cut-and fill roads is provided by a relief culvert that redirects runoff onto the fill-side of the road and onto a vegetated area

Additional lengths	Linkage type			
	No channel	Partial channel	Full channel	Direct
Total additional length (km)	0.00	1.10	8.6	0.30
Observed changes				
Total drainage length (km)	165	166	175	175
Drainage density (km/km ²)	4.4	4.4	4.6	4.63
Increase in drainage density (%)	0.00	0.66	5.87	6.02

Table 3: Calculated increase in drainage length and density by inclusion of linked pathways in the Cuttagee Creek catchment, NSW

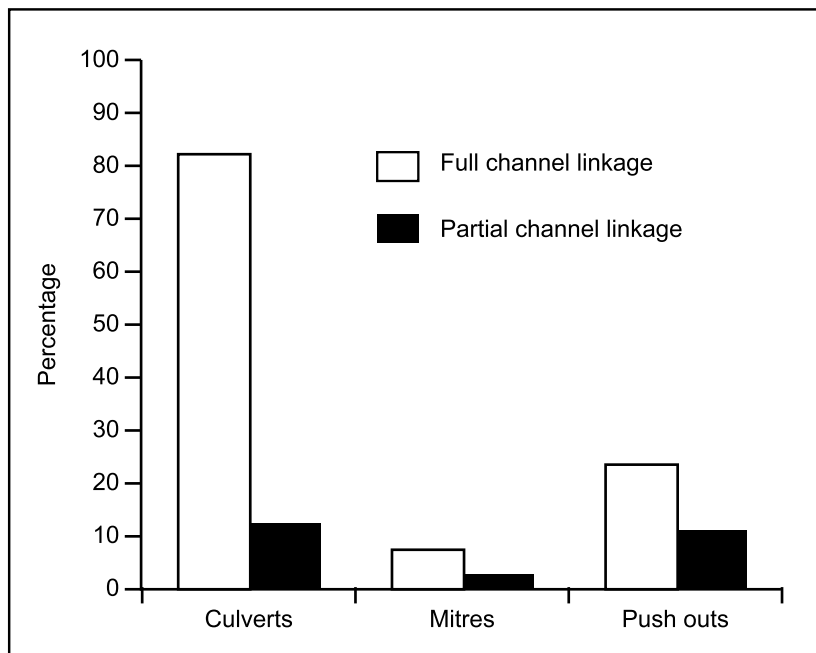


Figure 17: Variations in percentage of road outlets fully and partially linked to receiving waters via a channel according to major drain types - mitres, push-outs, and culverts

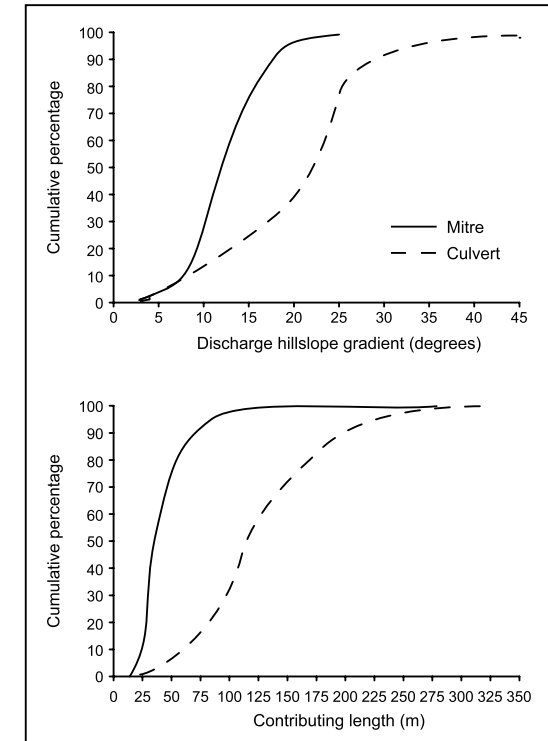


Figure 18: Differences between mitre drain- and culvert-road segments in the Cuttagee Creek catchment in terms of (a) gradient at the discharge hillslope and (b) contributing road length

- The average road-surface length drained by relief culverts (i.e. the contributing road length) is 110 m, compared with the 30 m of road surface contributing to mitre drains (Figure 18). Road length is proportional to runoff volume generated from the road surface, so at least 3 times more water discharges from relief culverts than from mitre drains.
- This larger volume of water from cut-and-fill roads is discharged onto hillslopes which are twice as steep as slopes adjacent to ridge-top roads (Figure 18). The combination of large contributing road length and steep hillslope gradient results in erosion and gully formation at the road-drainage outlet.



A cut-and-fill road showing cut-batter used to drain a segment of road in a mid-valley position where mitre drains cannot be installed

Preventing channelised sediment pathways

To predict where gully initiation is likely to occur along roads, we needed to define the critical limits of contributing road length and hillslope gradient above which gully development occurs.

We did this using a threshold relationship, where gullied and non-gullied road drainage outlets were separated according to a critical value of contributing road length and hillslope gradient at the discharge point (Figure 19). The resultant statistically fitted line successfully separates 74% of the road drainage points. The specific form of the relationship for the Cuttagee Creek catchment is:

$$L(m) = \frac{25(m)}{\sin\theta}$$

L(m) = maximum contributing length of the road segment.

25(m) = the calculated coefficient for the threshold curve for Cuttagee Creek.

θ = discharge hillslope gradient in degrees.

For example, for a road-drain discharging water onto a hillslope with a 15 degree gradient, the contributing length of road must not exceed 97 m or gully development will occur. As the hillslope gradient at the discharge point increases, the contributing road length must be reduced. On a hillslope with a gradient of 35 degrees at the discharge outlet, the contributing road length should not exceed 43 m or a gully will develop.

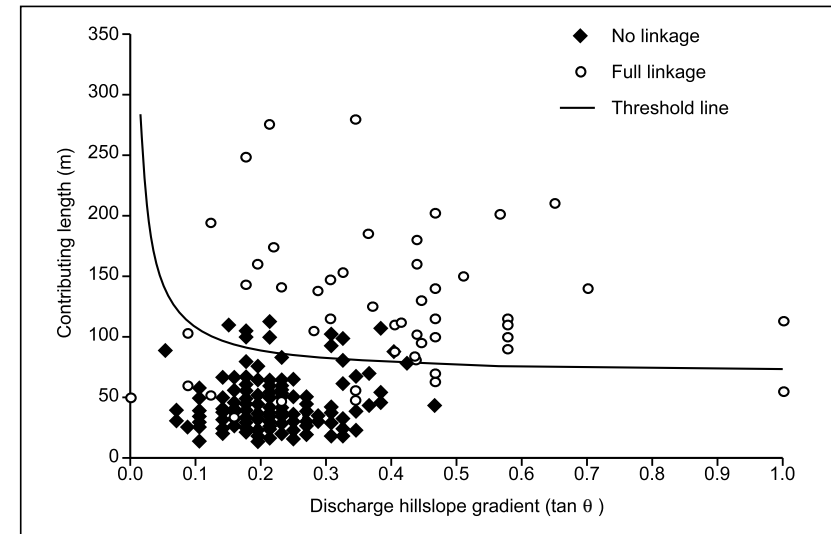


Figure 19: The threshold curve used to separate channelised and non-channelised flow pathways at road outlets. The curve is used to determine the contributing road lengths and discharge hillslope gradients above which gully development is likely to occur (note - tan θ of 1.0 is a slope angle of 45 degrees)

Management of channelised pathways

We can use the gully-formation threshold curve to construct a table of drain spacings that will prevent gully erosion at the drain outlet (Figure 20).

Current management guidelines for road drainage only focus on erosion of the road travelway or surface. Because preserving road-surface integrity is also important, we combined recommended road-drain spacings with those

predicted using our threshold analysis for preventing gully development at the road outlet. The table provides the minimum value predicted by both approaches.

This design table is applicable only to the study catchment. To be applied elsewhere, a threshold curve needs to be fitted, as spacing guidelines will vary in relation to the contributing road-length discharge gradient and soil

	Drain discharge hillslope gradient								
	2.5	5.0	7.5	10	15	20	25	45	
Road travelway gradient	0	-	110	95	90				
1	155	110	95	90					
2	155	110	95	90					
3	150	110	95	90					
4	125	110	95	90					
5	100	100	95	90					
6	90	90	90	90	85	80	75	75	
7	80	80	80	80	80	80	75	75	
8	70	70	70	70	70	70	70	70	
9	65	65	65	65	65	65	65	65	
10	60	60	60	60	60	60	60	60	
11	55	55	55	55	55	55	55	55	
12	50	50	50	50	50	50	50	50	
13	45	45	45	45	45	45	45	45	
14	40	40	40	40	40	40	40	40	
15	40	40	40	40	40	40	40	40	

Maximum contributing length
95m
for road gradient of 5°
and DHG 7.5°

Figure 20: Design table of appropriate drain spacings based on gradient of road travelway and gradient at discharge hillslope. The example given shows that for a road travelway gradient of 5 degrees and a discharge hillslope gradient (DHG) of 7.5 degrees, drain spacings should not exceed 95 m or a gully will develop at the drain outlet. Road travelway gradient is currently used for determining the appropriate drain spacings on roads in NSW. We strongly recommend that this design approach should include consideration of the gradient of the hillslope at the outlet (Note this is only applicable to the study catchment)

type within each catchment. The procedure is relatively straightforward, and the results not only improve our understanding of why gullies form at drain outlets, but also provide practical guidelines on appropriate road-drainage spacings.

Gully development is difficult - if not impossible - to remedy so prevention through appropriate road-drain spacing is clearly the best option.

Management of non-channelised pathways

As noted previously, many road-drainage outlets do not show gully development. However, water from these outlets still needs to be carefully managed to protect catchment water quality. The important question regarding such pathways is: will water from a discharge outlet, such as a cross bank or road drain, actually reach the stream network? (Figure 21)

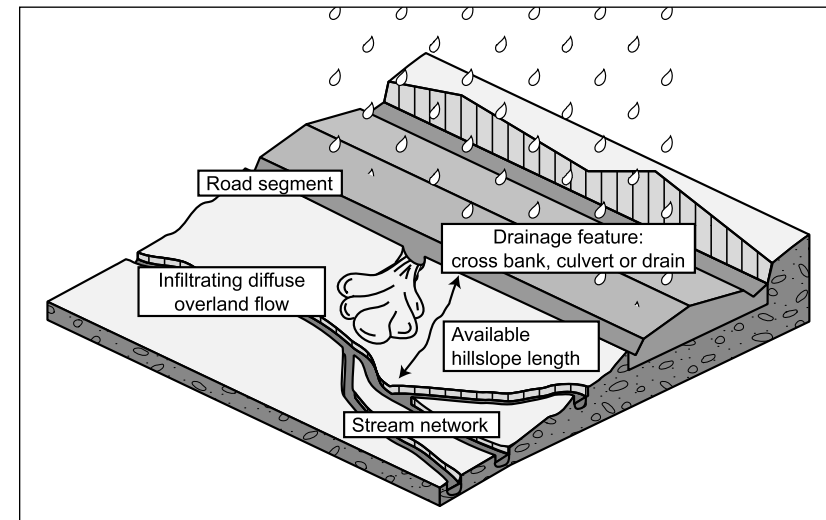


Figure 21: Factors that influence runoff delivery to a stream via non-channelised flow pathways: (i) Rainfall intensity on the road surface; (ii) Available hillslope length below a road outlet for runoff to infiltrate before reaching a stream; and (iii) Hydraulic properties of the hillslope, which influences the volume of water reaching a stream

Factors that influence runoff delivery in non-channelised pathways include the:

1. intensity and duration of a storm
2. infiltration properties of the discharge hillslope
3. proximity of the runoff source to a stream. This determines the dispersal area below a road drain that is available for runoff to infiltrate before it reaches a wet-area or stream channel.

Of these factors, only the third can be manipulated by management practices. Roads can be located in areas that maximise the dispersal area below the drain outlet. More importantly, runoff volume discharged at these outlets can be controlled by varying drain spacing.

SITING ROADS AWAY FROM STREAMS

Timber-harvest planning is the main factor determining the proximity of a sediment source to a stream channel. Forest managers make decisions about where to site roads, tracks, and log landings in relation to local topography and the stream network.



Feeder access road cut into hillslope in Cuttagee Creek - the road is drained by outfall drainage i.e. all water is diverted to the fill-side of the road by sloping the road outward

Permanent forest roads are usually planned before harvesting, and are designed to incorporate environmental attributes such as catchment terrain in accordance with engineering standards. In contrast, temporary roads and snig tracks are usually unplanned in relation to catchment attributes. Rather, they tend to be sited in accordance with site-specific limitations. For example, the siting of log landings, timber processing areas, and stream crossings is determined by drainage density, slope gradient, and access requirements for certain types of machinery (Figure 22).

We measured the available hillslope length below road-drainage outlets and cross bank outlets in both the Cuttagee Creek catchment and on selected forest compartments in the Eden

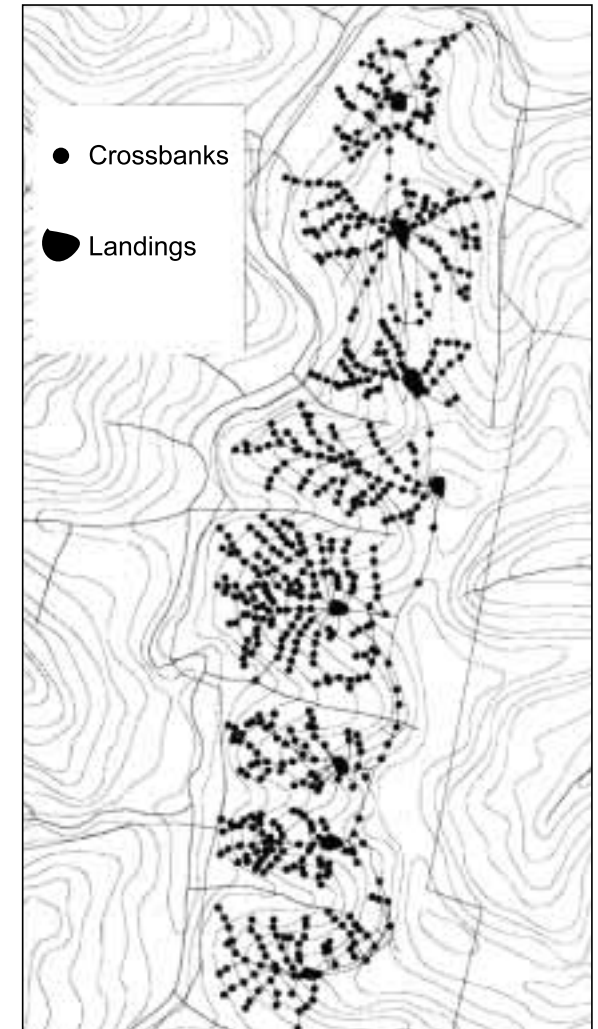


Figure 22: Example of a snig-track layout in the Murrumbidgee State Forest near Bermagui NSW. Note the way the log landings located on the ridge-lines dictate the pattern of tracks so that runoff is directed towards the drainage lines in this valley

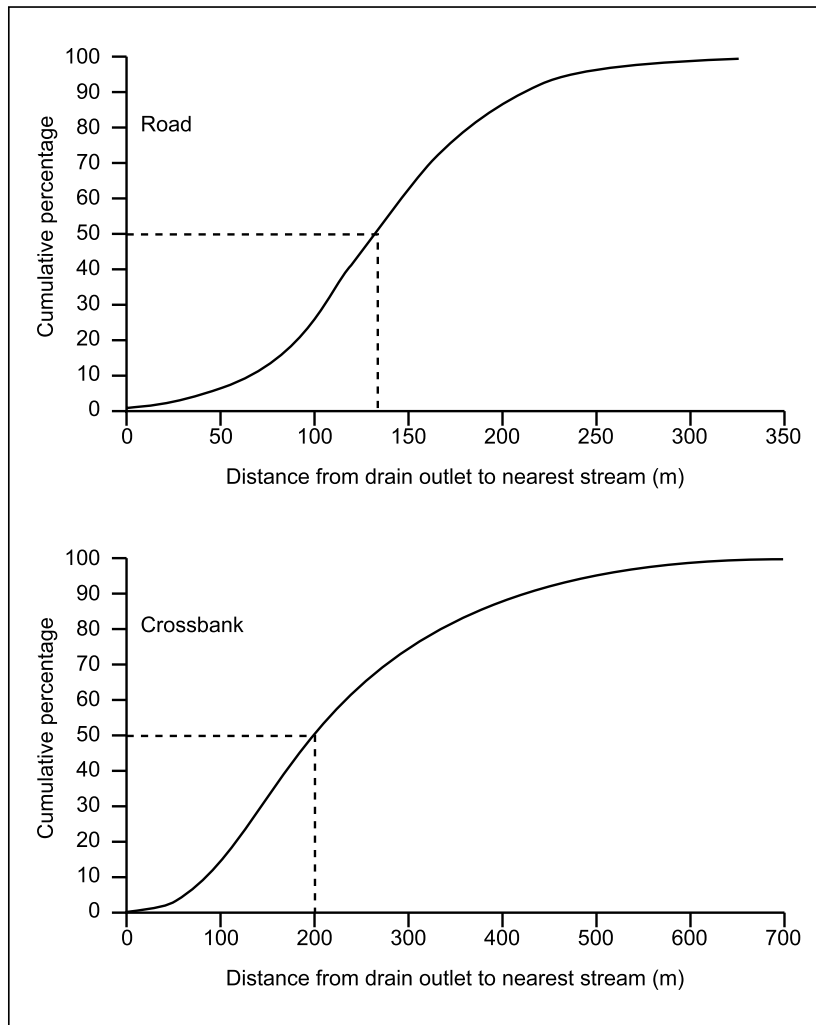


Figure 23: Available hillslope length for runoff to infiltrate (or flow distance to nearest stream) from road drainage outlets, which show a mean value of 136 metres, and snig tracks which show a mean value of 200 metres.

Forest Management Area. We found that 50% of the road drains were located within 100 m of a drainage line. In contrast, 50% of cross banks in a forest compartment near Bombala were placed within 200 m of a stream channel (Figure 23).

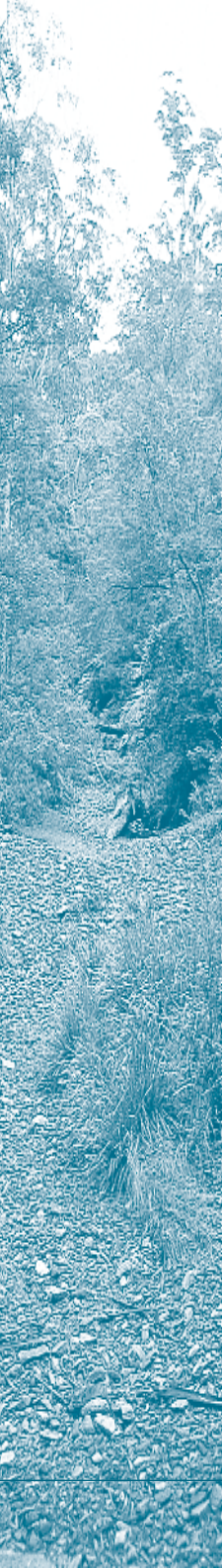
The planning and rehabilitation of forest roads clearly requires a systematic management system. The effectiveness of road management systems has increased rapidly due to recent advances in GIS (Geographical Information Systems) and GPS (global positioning systems) technologies, which allow for the storage, analysis, and display of road-related data. CSIRO Forests and Forest Products have developed and tested a Forest Road Management System (FRMS) that can be used to collect, store, and analyse forest-road information, and produce maps and reports describing the current condition of the road network (Winter and McCormack 1999). The estimated cost of implementing the FRMS in a large plantation area in NSW is \$15 per kilometre of road, or 95 cents per hectare of plantation.

SPACING DRAINS TO CONTROL RUNOFF DELIVERY

This section reports on a simple model for predicting the amount of runoff from a road or track that will reach a stream, and determining appropriate drain spacings to prevent runoff delivery. The model is based on comparing the volume of overland flow from the outflow of a cross bank with the volume that arrives five metres downslope. For the CRC study, data were obtained from rainfall-simulator experiments on snig tracks and general harvesting areas as described earlier.

Key findings

- The volume of water arriving 5 m down the hillslope was significantly less than at the cross bank outlet. This indicated that runoff was infiltrating on



the general harvesting area and that less water was being delivered downslope, even over the short distance of 5 m.

- For every 5 m of available hillslope below a cross bank or road-drainage structure, the general harvesting area reduced the overland flow by 336 ± 189 litres across all experimental sites. For example, on a 5 m wide road or track with a contributing length of 50 m during a 25 mm rainfall event, only 6% of the road-runoff volume traversed the 5 m downslope.
- We were able to construct a 'look-up' table (Figure 24) from the model to determine the probability of road/track runoff reaching the stream network for a series of forest compartments in the Eden Forest Management Area. It suggests the drainage spacing and available hillslope length required below the drainage outlet for 3 design storms of increasing intensity. We set the allowable risk of some overland flow reaching the stream at 5% - that is, 5% of storms may result in overland flow reaching the stream.
- As an example, for the equivalent of a 1-in-2 year storm generating 13 mm of runoff with cross banks spaced at 10 m intervals, at least 18 m of available hillslope length would be required below the outlet to ensure that runoff does not reach a stream. With increasing rainfall intensity, available hillslope length increases or cross bank spacing decreases. The figure is used as a demonstration only. An agreed risk of overland flow reaching the stream and design storms could be used with this methodology to produce actual design curves.
- Runoff delivery in non-channelised pathways can thus be controlled by manipulating runoff volume (as a function of contributing length of road) and hillslope area over which the runoff can be spread below the drainage outlet (i.e. available hillslope length).

- To prevent overland flow and associated fine sediments reaching a stream, the contributing road or track length should be reduced in areas close to the stream network.

Runoff contributions from roads and tracks to streams can be minimised by siting drains with the greatest available hillslope length below them to maximise runoff infiltration.

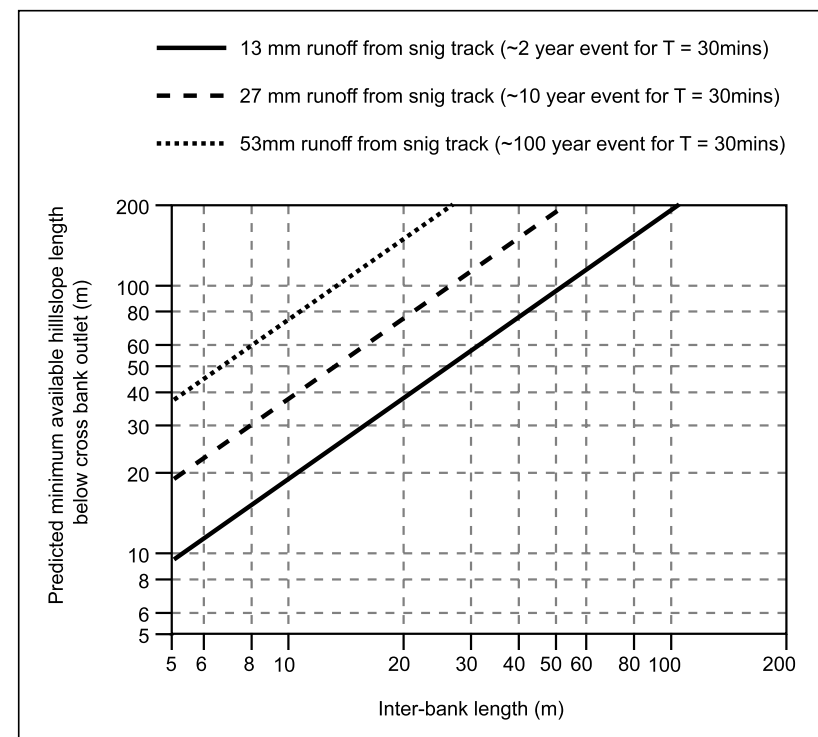


Figure 24: 'Look-up' table designed to predict the minimum available hillslope length below a road drainage outlet required to prevent runoff reaching a stream via non-channelised flow pathways. For example, for a 1-in-2 year storm with a cross bank or drain spacing (inter-bank length) of 10 m, a distance of ~20 m is required below the outlet to ensure runoff will not reach the stream. This distance increases as rainfall intensity increases; alternatively, the cross bank or drain spacing must be reduced

HOW MUCH SEDIMENT DO THESE PATHWAYS DELIVER TO STREAMS?

We quantified sediment delivery ratios for both channelised and non-channelised pathways at road outlets in the Cuttagee Creek catchment.

Key findings

- Sediment concentrations in runoff entering a gully from a road outlet showed no change with distance downslope. There was no net deposition or reduction of runoff within the gully pathway (Figure 25).
- About 85% of the material delivered to channelised pathways was transported downslope to the next adjoining channel. Thus, for every 10 tonnes of sediment delivered to a gully from a road culvert, about 8.5 tonnes would be delivered to the adjoining channel downslope.
- About 39 tonnes of material was generated from the surfaces of the road network in Cuttagee Creek during a 1-in-100 year storm event of 30 minutes duration. Of this, about 7 tonnes or 17% was delivered directly to channels via gullied pathways.
- In contrast, sediment concentrations in runoff in non-channelised pathways reduced as the flow spread and slowly moved downslope. This indicated net deposition which occurred as runoff volume decreased through water infiltrating the hillslope.
- About 10% of the material entering a non-channelised flow path was delivered to the bottom of the hillslope during an equivalent 1-in-100 year rainfall event.

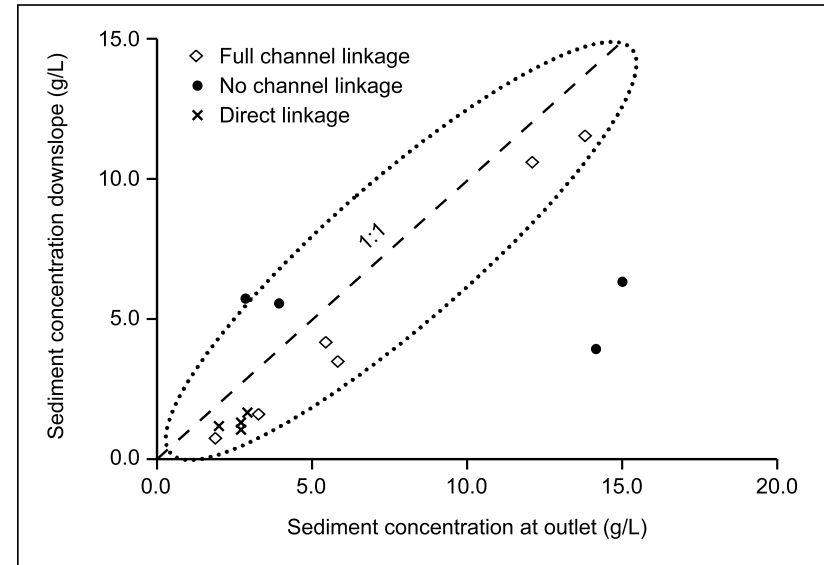


Figure 25: Differences between sediment concentrations from a road drain and from downslope for channelised, non-channelised, and direct flow pathways. Points on, or close to, the 1:1 line indicate little change in sediment concentration, and hence no deposition or storage. These are typical of channelised pathways. Direct-flow pathways also show little change because the distance between the road outlet and the stream is typically short, and does not allow for much deposition or reduction in runoff. Non-channelised pathways show deposition or, in some cases, if loose material such as ash or charcoal is available for transport, sediment concentrations may even increase (Cuttagee Creek)

III. BEST MANAGEMENT PRACTICES

The previous two sections reported on sediment sources and pathways through forestry environments. Best management practices are applied in every logged forest to manage these sources and pathways. These practices include:

- establishing riparian buffer-strips of variable width
- harvesting alternate coupes
- siting and designing roads and road crossings to minimise sediment input
- restricting logging activities in relation to coupe slope and soil type

We need to be confident that such measures indeed function to prevent sediment delivery to streams and, most importantly, do not enhance delivery rates.

IS ROAD AND TRACK DRAINAGE EFFECTIVE?

As noted earlier, roads and tracks are key sources of runoff and sediment. We examined the effectiveness of road and track drainage methods in this project.

Key findings

- The most damaging aspect of road drainage was poor drain spacing, which resulted in gully development at road-discharge outlets and maximum linkage between a sediment source and stream.
- Road drains, such as mitres, effectively slowed runoff and induced sediment deposition within the drain structure. Differences in sediment yield between road drain inlets and outlets indicated that up to 50% of eroded material was deposited (Figure 26). These areas contain trash and debris from previous rainfall events, and sediment deposition occurs as runoff velocities reduce.

- Drains and roadside ditches must be kept rough to slow runoff and induce deposition. Long, narrow and clean drains will act to concentrate the flow and reduce friction and roughness, which would otherwise slow the flow and reduce sediment loads. **Keep road drains wide, rough, and 'dirty' to reduce flow and trap sediment.**
- Cross banks draining forest snig tracks are effective in trapping coarse-grained sediment. About 50% of eroded sediment was trapped at the base of cross banks across all the experimental sites.

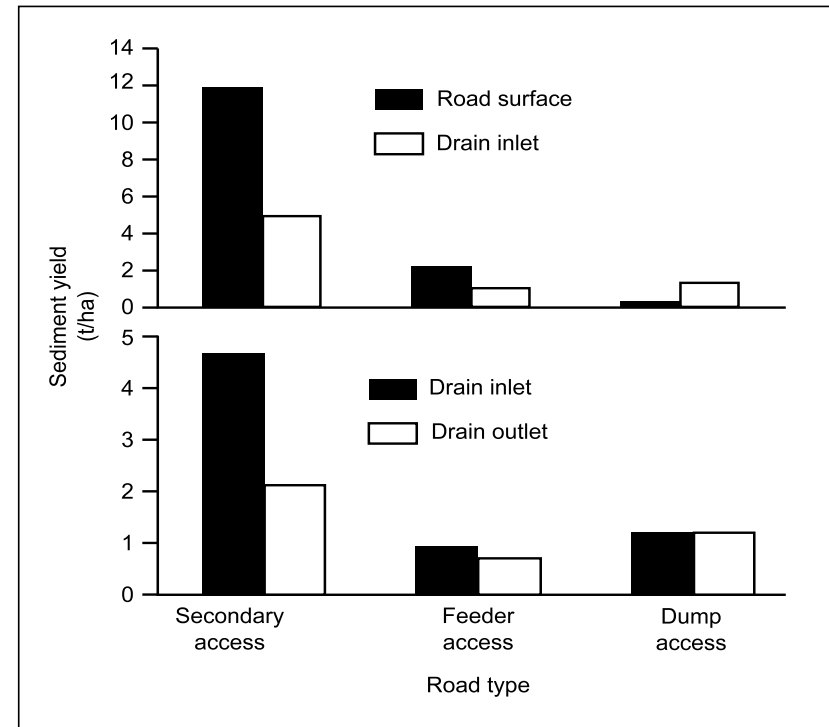


Figure 26: Sediment yield differences at inlet and outlet points of mitre drains in the Cuttagee Creek catchment. Reductions in yields indicate deposition and storage of material within roadside ditches and the drains themselves, suggesting that these areas are important in trapping sediment and reducing the sediment load delivered downslope

- Cross banks are not effective in trapping fine-grained sediment. The more silt and clay in runoff, the higher the sediment-delivery ratio.
- Exposure of fine-grained, dispersive subsoils should be minimised during cross bank construction.
- Rather than risk exposing fine-grained subsoils, runoff volume should be reduced by minimising the contributing area of each snig track (i.e. drains should be placed closer together).
- Cross banks should not be constructed to act as sediment traps or dams. We recommend that cross banks should be at least 0.50 m but are not required to exceed this height (Figure 27).

- If taking soil for the cross banks risks exposing subsoils, reduce the spacing of banks to minimise flow.
- ***Avoid building cross banks too high and blading off - i.e. exposing subsoils in mounding soil for cross bank construction.***

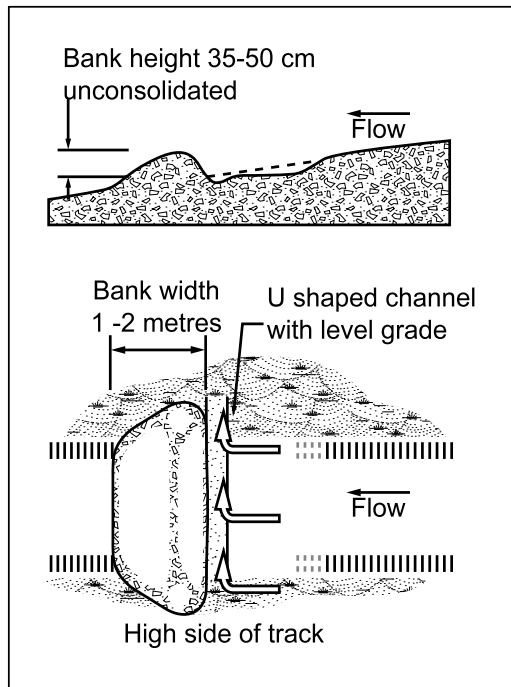


Figure 27: Cross bank (water bar) construction to an average height of 0.5m, designed primarily to redirect flow from the track onto the adjacent hillslope

What are cross banks and water bars for?

Over the years, methods of installing road and track drainage structures have changed, leaving contractors and operators confused about the specific purpose of erosion-control and drainage devices. Through the course of the project, we have observed many instances of poor road and track drainage, resulting from operator confusion and poor communication. A classic example is cross bank (or water bar) drainage of forest snig tracks, which we have seen constructed as high as 1 m and as low as 20 cm.

Cross banks serve 4 functions in controlling sediment movement within forestry compartments:

1. define the specific catchment area of the snig track, so that overland flow does not develop enough energy to cause gullies
2. reduce sheet and rill erosion through reduction in slope length
3. deposit some sediment as flow reduces at the cross bank
4. redirect overland flow into the adjacent hillslope so that further sediment deposition may take place

TRAPPING SEDIMENT IN VEGETATED AREAS

One of the most effective ways of reducing runoff volume and sediment loads is to disperse the flow onto a vegetated area. While this is the principle behind the placement of buffer or filter strips around a stream channel (see box), it can also be applied elsewhere in the catchment.

We examined the effectiveness of dispersing runoff to reduce sediment loads at both cross bank outlets and in buffer or filter strips in selected sites in northern NSW (Figure 28).

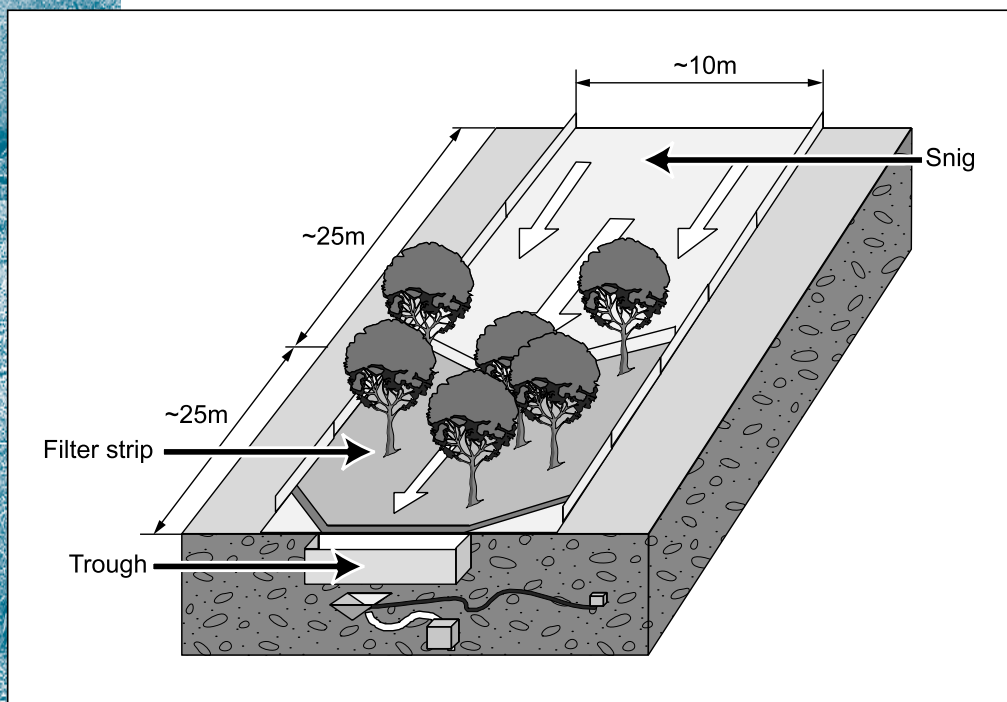


Figure 28: Layout of experimental plot for filter-strip study, Coffs Harbour, where an exposed snig track fed a vegetated area. Sediment trapping and runoff reductions were measured within this area

The function of forest filter- (or buffer-) strips

The terms buffer-strip and filter-strip relate to vegetated areas adjacent to stream channels of designated width. Filter-strip is the term used most commonly in Victoria to describe the additional protection strip around a buffer strip where machinery entry is permitted. All machines are excluded from buffer-strips.

Vegetated areas in forests serve several functions:

- to reduce the flow of sediment and associated pollutants from key source areas, such as tracks and roads, to streams
- to reduce the movement of soluble pollutants from hillslope to stream
- to maintain stable channels
- to reserve near-stream vegetation for ecological purposes

Why are vegetated areas so effective in trapping sediment?

- the roughness of a vegetated area - largely determined by the density of vegetation and obstacles such as logs, fallen debris, and leaf litter - acts to slow surface-flow velocities and induce sediment deposition
- high hydraulic conductivities (soils in which surface water drains through the soil instead of running off) within vegetated areas reduce the delivery of overland flow and pollutants to streams

Key findings

- Dispersing runoff from cross bank and road outlets onto vegetated areas is effective in reducing both total runoff and sediment loads (see Figure 9).
- Between 80% and 90% of the sediment entering two undisturbed vegetated filter strips was trapped, confirming their effectiveness in reducing sediment loads.
- Severe disturbance of the filter strip by successive passes of a bulldozer reduced sediment trapping to 40%.
- The development of rills in the wheel-ruts of heavy logging machinery concentrates the flow, increasing flow velocities and sediment transport capacities even in vegetated areas. Prevention of channelised or concentrated flow pathways is essential.
- **Disperse water onto vegetated areas (even if partially disturbed) wherever possible. Consider the general harvesting areas as a large hillslope buffer that can be used to reduce runoff volume and sediment loads.**

Minimising surface disturbance

The differences in the degree of compaction, infiltration, surface runoff, and erosion rates between the snig tracks and general harvesting area highlight a basic, but significant, point about minimising surface soil disturbance - the more soil disturbed, the greater the availability of soil for delivery to streams. Thus, **limiting surface-soil disturbance through careful planning and location of highly disturbed areas is essential.**

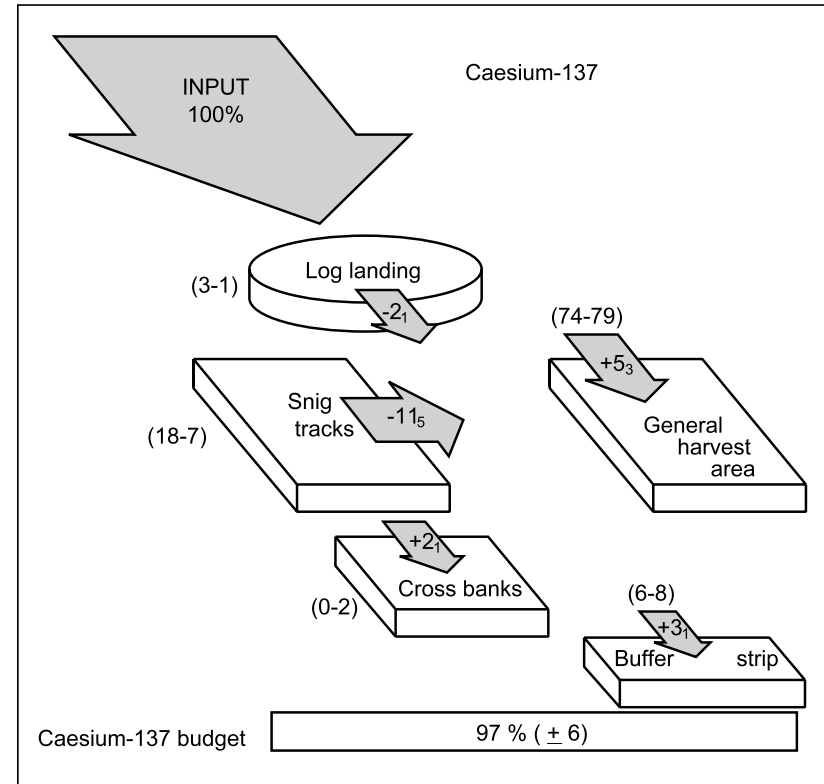


Figure 29: Tracer budget showing redistribution of Caesium -137 after harvesting plus 6 years of erosion and deposition. Initial caesium input to the catchment was normalised to 100%. The first value in brackets represents the pre-harvesting amount of caesium in each element as a fraction of initial input. The second value represents the fractional amount post-harvesting plus erosion. Values inside the arrows represent the amount either eroded from, or deposited onto, each element. The smaller figures represent the uncertainty, or degree of confidence in the number. The value in the bottom box represents the sum of all tracer amounts retained in the catchment after harvesting

DO BEST MANAGEMENT PRACTICES PROTECT THE WHOLE CATCHMENT?

Previous assessments on the success of selected best management practices (BMPs) were based on rainfall-simulator and tracer studies at the hillslope or plot scale. The effectiveness of all existing BMPs for controlling sediment production and delivery at the *catchment scale* needs to be tested. The tracer data described previously can be used to determine whether or not harvesting resulted in a net loss of soil material from the catchment.

In this project, we constructed a catchment-scale, tracer-based sediment budget using the following procedure. The amount of ^{137}Cs in the catchment before harvesting was calculated as 61.1 ± 3.1 MBq, which we normalised to 100% (Figure 29). The total amount of ^{137}Cs present in the catchment after harvesting was calculated as 59.0 ± 3.6 MBq. The pre- and post-harvest values of ^{137}Cs are not statistically different, and represent a total net tracer recovery of 97 ± 6 %. A total of 2.1 MBq was unaccounted for, which is within the uncertainty limits of the pre-harvest budget of 61.1 ± 3.1 MBq.

Key findings

- All ^{137}Cs material was accounted for onsite (within uncertainty levels), indicating that the BMP strategies applied were effective at the catchment scale.
- The general harvesting area retained the greatest amount of remobilised soil material. However, the general harvesting area comprised 74% of the study area, and the buffer-strip only 6%. Thus, on an area-weighted basis, the buffer-strip retained 5 times more ^{137}Cs than the general harvesting area.

- This highlights the importance of buffer-strips in retaining sediment and nutrient fluxes within the catchment.

In conclusion, best management practices (BMPs) were effective at the whole-catchment scale. This raises the question: 'Are the increases in sediment yields reported elsewhere the result of channel erosion and not hillslope erosion?'. Channel form and process changes caused by logging is an area for future research in Australia.

WHAT CHALLENGES FACE THE LOGGING INDUSTRY IN TERMS OF WATER PROTECTION?

This CRC research project has clearly established the positive impact that management practices can have in reducing erosion rates and sediment delivery associated with forest harvesting and roads.

The research and its outcomes have also focused our attention on the critical problem areas in terms of sediment generation and delivery - forest roads and tracks - and have provided practical, applicable suggestions for effective management of these surfaces. Assessing the state of the existing forest road and track network should be a priority, especially for the design and siting of road-drainage structures.

We believe that this research has also challenged traditional thinking on soil erosion and water-pollution management, which has been heavily influenced by processes and data from agricultural environments.

The connection between water pollution and the runoff capacity of a source area is now much better understood in forestry environments.

This understanding has been derived from data that specifically considered the unique attributes of forest environments in terms of cover, soil, and hydraulic properties.

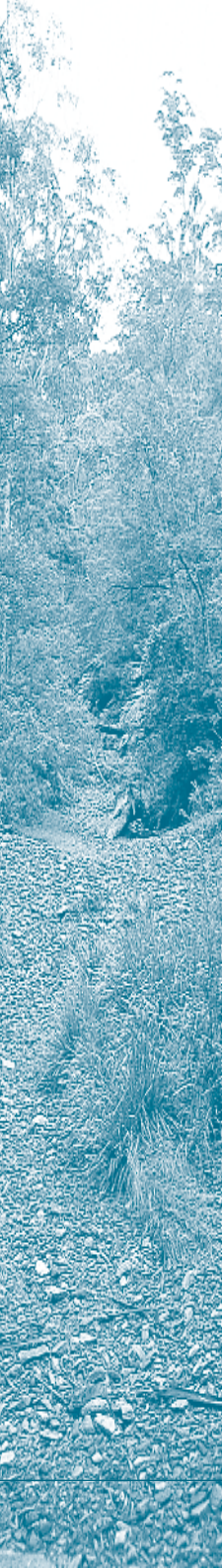
The major challenge for the logging industry is now one of communication and education - to provide the training that will underpin the successful management of logged catchments for the protection of soil and water. A number of existing documents are designed to assist in this process. In all Australian states there are codes of forest practice or formal management guidelines that define standards for forest soil and water management, and set out prescriptions and guidelines defining best management practices.



Forestry personnel, community groups, and environmental groups attending a CRC rainfall simulator demonstration, Bermagui, NSW

These codes apply in most states to logging on public and private land. In NSW, forestry operations on state land are also regulated by the EPA (Environment Protection Authority) through a pollution control licence.

Prescriptions and guidelines from the codes and licences, which are applied at a local level in harvest plans, are prepared prior to logging operations. These documents incorporate information on yield, access, and application of prescribed management practices to the specific conditions of a site. This process involves designation of erosion-hazard classes and drainage-line categories. This is the stage at which decisions are made on filter strip width, access-road alignment, location of drainage measures, and log-dump location.



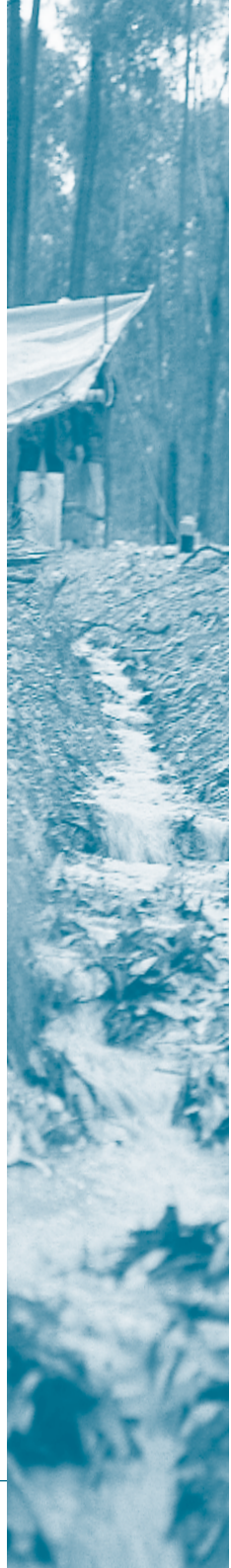
A review on the perceived success of these documents, specifically the code of forest practices, indicated that more directed and specific training is required in some states (O'Shaughnessy 1995). Logging contractors, usually under the supervision of agency or company officers, are responsible for ensuring compliance with management practices prescribed in codes and harvest plans. It is essential, therefore, that officers involved in field operations have at least a basic understanding of forest soil and water management. In some states, government agencies have now introduced accredited training programs in soil and water management for both contractors and supervisors.

From the high attendance numbers at the workshops and field days held throughout this project, we conclude that there is a genuine willingness among forestry personnel, and community and environmental agencies to learn and incorporate new science and technologies into the management and protection of Australia's native forests. This positive attitude provides a good foundation for introducing appropriate changes to the management of Australia's native forests during the next few years.

SUMMARY OF RESEARCH PROJECT

Through this project, the CRC has:

- measured differences in runoff and sediment generation rates from forest roads, snig tracks, and general harvesting areas (GHAs)
- explained how erosion rates vary with such factors as soil type and recovery time
- classified the main sediment-delivery pathways connecting source areas with receiving waters
- presented predictive methods for determining where these pathways are likely to occur
- presented management guidelines for controlling sediment delivery in channelised and non-channelised pathways
- examined the effectiveness of current best management practices - such as road and track drainage, sediment trapping in filter strips, and minimising soil disturbance - and provided practical suggestions for improvement
- provided new knowledge to assist forest managers in recognising hot-spots or high-risk areas in logged catchments





GLOSSARY/ABBREVIATIONS

Becquerel – unit of measurement of radioactivity (one nuclear disintegration per second)

BMP – best management practices

¹³⁷**Cs** – Caesium -137, a by-product of nuclear weapons testing

Cross banks – mounds of soil created by scraping of snig tracks

DHG – Discharge hillslope gradient

Filter-strips or buffer-strips – intact belts of forest adjacent to streams to control water quality

FMA – Forest Management Area

GHA – general harvest area

GIS – Geographical Information Systems

Linkage – degree to which sediment delivery pathways are linked to streams (e.g. full channel linkage, partial linkage, direct linkage, and no linkage)

Log landings – sites where logs are dumped to be stripped of bark and loaded onto trucks

SDR – sediment delivery ratio - proportion of eroded sediment actually delivered to streams from sediment source

Snig track – pathways created by bulldozers to carry logs to log landings

FURTHER READING

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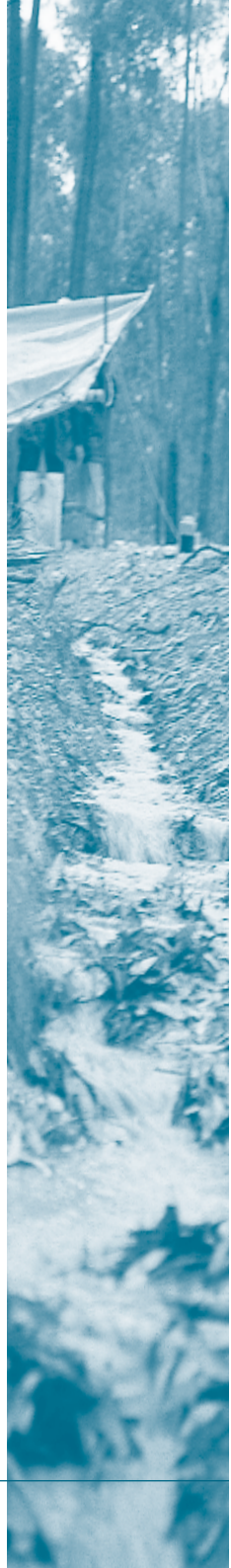
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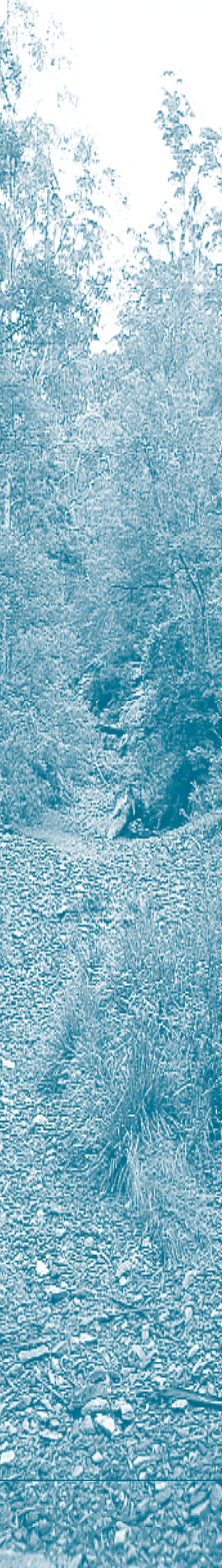
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CENTRE OFFICE

Department of Civil Engineering Monash University Clayton VIC 3800 Australia
Telephone +61 3 9905 2704 Facsimile +61 3 9905 5033 <http://www.catchment.crc.org.au>



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- Department of Land and Water Conservation, NSW
- Department of Natural Resources, Qld
- Department of Natural Resources and Environment, Vic
- Goulburn-Murray Water
- Griffith University
- Melbourne Water
- Monash University
- Murray-Darling Basin Commission
- Southern Rural Water
- The University of Melbourne
- Wimmera Mallee Water

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